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AN EVAPORATING FILM CALORIMETRIC ENTHALPY PROBE

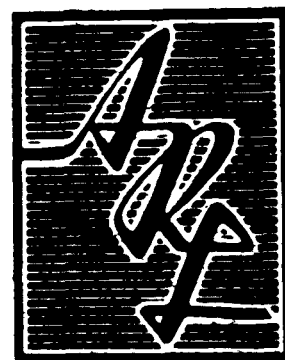
F. C. HAAS

CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO 21, NEW YORK

FEBRUARY 1963

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ARL 63-47

AN EVAPORATING FILM CALORIMETRIC ENTHALPY PROBE

F. C. HAAS

**CORNELL AERONAUTICAL LABORATORY, INC.
BUFFALO 21, NEW YORK**

FEBRUARY 1963

**CONTRACT AF 33(657)-7774
PROJECT 7063
TASK 7063-01**

**AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This report was prepared by Cornell Aeronautical Laboratory, Inc., of Cornell University, Buffalo 21, New York under Contract AF 33(657)-7774. The research reported herein was accomplished on Task 7063-01, "Research in Heat Transfer Phenomena" of Project 7063, "Mechanics of Flight." This program was sponsored by the Aeronautical Research Laboratories, Office of Aerospace Research, United States Air Force. The project was under the cognizance of Captain T. Andrada, Task Scientist and Mr. Erich Soehngen, Chief of the Thermo-Mechanics Research Laboratory, ARL.

The studies presented began in November 1961 and were concluded in December 1962. They were performed by the Applied Hypersonic Research Department of Cornell Aeronautical Laboratory, Inc.

The aid of Mr. J. R. Shoemaker in development of the gas-phase composition-measurement instrumentation and Mr. A. K. Ashby in fabrication of the research model of the enthalpy probe is gratefully acknowledged.

ABSTRACT

A calorimetric enthalpy probe of small size, capable of continuous operation in a high temperature, high heat flux environment, such as an arc, is described. The instrument operates by removing a sample from a hot gas stream and cooling it by evaporative film cooling until the temperature of the gas sample is low enough for measurement by conventional means. The composition of the cooled gas sample is measured and the total enthalpy of the hot gas entering the instrument is determined by an energy balance technique. The structure of the instrument may be maintained at a tolerable temperature level by forced convective cooling or by evaporative film cooling.

The instrument has been compared for accuracy with gas temperature measurements made by conventional techniques at temperatures between 2100 and 4300 °R. These tests, using nitrogen as the test gas and water as the evaporative coolant, have shown an average deviation of 2.3 percent between the methods of measurement.

An instrument with an outside diameter of 0.1" has been fabricated and tested. This instrument is designed to measure an enthalpy of 15,000 Btu/#. To complement the enthalpy determination instrument, an instrument for continuous measurement of the gas-sample composition has been developed.

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SYMBOLS

A	Area (cm^2) (ft^2)
A, A', A''	Defined by Equation (16)
C	Capacitance ($\mu\mu f$)
C_p	Specific heat ($\text{Btu}/\#^\circ\text{F}$)
D	Diameter (ft)
D	Dielectric constant
D_{a-b}	Diffusion coefficient (ft^2/sec)
d	Spacing between plates of capacitor (cm)
d	Diameter of core of radiating gas (ft)
H	Enthalpy ($\text{Btu}/\#$)
K	Constant defined by Equation (24)
k	Thermal conductivity ($\text{Btu}/\text{hr ft}^2\text{F}/\text{ft}$)
\bar{k}	Boltzmann's constant
L	Length (ft)
L	Radiative beam length (ft)
Le	Lewis Number
M	Molecular weight ($\#/\# \text{ mole}$)
N	Avogadro Number
Nu	Nusselt Number
P	Pressure ($\#/\text{in}^2$)
P_r	Prandtl Number
Q	Rate of energy transfer (Btu/hr)
q	Heat flux ($\text{Btu}/\text{ft}^2 \text{ sec}$)

SYMBOLS (Cont.)

R	Radius of electrode (ft)
r	Radius (ft)
Re	Reynolds Number
T	Temperature ($^{\circ}F$)
u	Velocity (ft/sec)
W	Mass flow rate (#/hr)
x	Distance (ft)
y	Mass fraction (#/# mixture)
Y	Mole fraction (# mole/# mole mixture)
α	Polarizability of molecule (cm^3)
δ	Liquid film thickness (ft)
ϵ	Emissivity
λ	Heat of vaporization (Btu/#)
μ	Dynamic viscosity (#/ft sec)
μ	Permanent electric dipole moment (e. s. u.)
ν	Kinematic viscosity (ft^2/sec)
ρ	Density (#/ft ³)
σ	Stefan-Boltzmann constant

SUBSCRIPTS

$A, B, C, D, E, F, G, H, I$ Denotes location in Figures 1 and 2

c	Denotes coolant
CO_2	Denotes carbon dioxide
g	Denotes gas

SYMBOLS (Cont.)

H_2O	Denotes water
i	Denotes interface
mix	Denotes mixture
N_2	Denotes nitrogen
o	Denotes entry
o	Denotes standard conditions
sc	Denotes structure coolant
T	Denotes total
V	Denotes vapor
$-$	Denotes average

I. INTRODUCTION

Experimental diagnosis of high-temperature gas streams, such as occur in electrical arcs, is limited by a lack of usable instrumentation. Techniques considered conventional in low temperature operations are not generally usable due to the high-temperature environment in which the instrument must operate. Total enthalpy of a high-temperature gas stream is a parameter of interest because it is one of the state functions of the gas and because it is the driving potential in energy transfer processes. At present there are two general techniques of enthalpy measurement in large-area, high-temperature gas streams. One technique utilizes measurement of heat transfer to a surface of designated geometry and temperature and via calibration techniques and knowledge of the heat transfer mechanism, the total gas enthalpy is computed. The second technique utilizes a direct calorimetric measurement of the total enthalpy by collecting a sample of gas and cooling it in a heat exchanger. The total enthalpy of the inlet gas is obtained by making an energy balance on the heat exchanger. The coolant in the heat exchanger serves the dual purpose of cooling the gas sample and maintaining the instrument surfaces at low temperature in order that structural integrity is maintained. Due to the dual source of energy in the coolant, a calibration is required to evaluate the energy of the gas sample. This calibration is accomplished by pulsing the gas flow in the exchanger to determine the energy content of the coolant when a gas sample is not being cooled. This calibration technique makes the operation of this instrument intermittent.

For research in small area gas streams such as arcs, it is highly desirable to have a small sensing instrument to minimize any disturbance of the gas stream. In addition, it is highly desirable to have a continuously

operating instrument. The first measuring technique described above does not lend itself to miniaturization due to the instrumentation required in the vicinity of the sensing area. The second technique described, calorimetric measurement, lends itself to some miniaturization, but in its present form is noncontinuous. To make this technique continuous requires as a minimum that instrumentation be placed at the sampling tip which in turn hampers miniaturization.

The objective of this program has been to conduct research leading to the development of an instrument capable of continuous measurement of local enthalpies in a high temperature gas stream, such as an arc. The general technique of enthalpy measurement employed is calorimetric. The gas sample is cooled by evaporation of a liquid coolant into the gas stream. The liquid film protects the heat exchanger surface from excessive temperature. The structure of the instrument is maintained by forced convection cooling or transpiration cooling. The total enthalpy of the gas is computed from knowledge of the temperature and composition of the cooled gas sample.

The instrument has been considered for operation in the vortex-stabilized arc at the Aeronautical Research Laboratories. The research model of the instrument has been designed for use in this arc facility operating at a gas pressure in the vicinity of one atmosphere and at enthalpy levels between 1100 and 14,000 Btu/#, for nitrogen flow rates between 0.01 and 0.125 pounds per second.

II. LITERATURE SURVEY

An initial goal of this program was an evaluation of methods of determining the total enthalpy of high temperature gas streams. A survey of the open literature was conducted in which the following abstracting sources were consulted: Chemical Abstracts 1950-1959, Nuclear Science Abstracts 1947-1962, Physics Abstracts 1950-1959, Engineering Index 1958-1960, Applied Science and Technology Abstract 1950-1961, Ceramics Abstracts 1950-1960, ASTIA Technical Abstract Bulletin 1960-1962, and Heat Transfer Bibliography of International Journal of Heat and Mass Transfer 1960-1962. The literature collected in this survey has been organized into the following general topics and is listed in Appendix A as follows:

- I. Methods of Static Temperature Measurement in High-Temperature Gas Streams
- II. Methods of Total Temperature or Enthalpy Measurement in High-Temperature Gas Streams

A great majority of the references uncovered are concerned with measurement of gas temperature as opposed to direct measurement of gas enthalpy. The enthalpy may be inferred from knowledge of temperature if sufficient thermodynamic data are available. In the true thermodynamic sense, temperature exists only for a system in thermal equilibrium. When temperature is used as the parameter to describe the thermal state of the gas, care must be taken to assure that the system is in thermal equilibrium. If the system is of the nonequilibrium type, as may readily occur in arc heated gases, the specific temperature component measured must be identified, since by virtue of being in nonequilibrium, the temperatures associated with each mode of energy content are not equal. For example, under nonequilibrium conditions the measured temperature may be due to rotational energy, vibrational energy, electronic energy, or any one of a number of particular energy definitions depending upon the selectivity of

the sensing technique. Determination of gas enthalpy from temperature data in a nonequilibrium system must include consideration of all component temperatures. In an equilibrium system, knowledge of any one component temperature is sufficient information.

Prominent among the component temperature measurements are optical and radiation techniques. These methods are advantageous in that the gas stream is not physically disturbed because the sensor is placed outside the gas stream. Disadvantages stem from the fact that the measured quantity is averaged over several temperature regions between the sensor and the core of hot gas. Localized values may be inferred by application of several assumptions and use of an Abel integral technique. Errors may be introduced by self-absorption, scattering, chemiluminescence, and many times only the static temperature is measured. References dealing with optical and radiation techniques are listed in subclass I of the literature survey given in Appendix A.

More convenient properties for heat transfer analyses are the total temperature and the total enthalpy of a gas stream. Relatively few references to total temperature or enthalpy measurements in high temperature gas streams have been located. References dealing with total temperature or total enthalpy measurement techniques are listed in subclass II of Appendix A. Measurements of this type are advantageous in that they allow direct measurement of local values if the probe size is small to minimize stream disturbance. Since the instrument must be inserted into the gas stream, the disadvantage of maintaining structural integrity arises.

Thermocouple techniques of measuring high gas temperatures are described by several authors. Due to structural material limitations the present upper limit of usefulness is 6000 °R. The cooled tube pyrometer (90)* relates a heat transfer coefficient to the total gas temperature and is

*References of this section are listed in Appendix A.

limited by cooling techniques and need for knowledge of gas-stream transport properties at extremely elevated temperatures. A fast response heat-flux probe (87) may be used to measure gas temperature if knowledge of gas stream molecular weight is available. The need for considerable instrumentation near the tip of these heat-flux probes appears to limit the degree of miniaturization possible. The pneumatic probe (91, 98, 102, 103, 105) has shown satisfactory operation at temperature levels where dissociation and ionization are not prevalent. Effects of dissociation and ionization at the nozzle entrance and nozzle cooling have not been resolved. Again the provision of sufficient cooling and miniaturization of the instrument appear as significant problem areas. Measurement of the total enthalpy of a high energy gas stream by a calorimetric technique in which a sample of the gas is cooled to a low temperature, which can easily be measured by conventional thermocouple techniques, has been described in References 94, 95, 96 and 97. Previous work at CAL (96, 97) has shown this method to be accurate to one percent at temperature levels where thermocouples may be used to measure gas temperature. This measurement technique is a discontinuous method since the measurement is obtained by making energy balance measurements with and without gas flowing through the instrument. For this type of instrumentation, the requirement of small size is not consistent with continuous operation since continuous operation requires as a minimum the placement of temperature sensing elements at the tip of the instrument.

III. EVAPORATING FILM CALORIMETRIC ENTHALPY PROBE

The evaporating film calorimetric enthalpy probe is based on the technique of making an energy balance around a heat exchanger which cools a hot gas by evaporating a liquid into the gas. Measurement of gas composition and temperature as it leaves the exchanger provides the major thermal information required for computation of entering gas enthalpy.

A general schematic diagram of the instrument is shown in Figure 1. Hot gas enters the probe at A. The film of liquid coolant (B) is used to cool the gas stream by evaporation of the liquid into the gas stream. At point C, the temperature of the gas mixture (gas sample plus coolant vapor) is sufficiently low that the temperature may be measured by conventional means. For purposes of the energy balance, a sample of the gas mixture is taken at C and this sample is analyzed for composition. The bulk of the gas mixture and the remaining liquid layer are drawn from the probe via tube D. The transpiration film coolant enters at E and its inlet temperature is measured at F. The external surfaces of the instrument (G) may be protected from the high heat flux environment by transpiration cooling or by forced convection.

Figure 2 shows a half-section of the thermodynamic system of interest. Writing an energy balance about the system yields:

$$W_{g_A} H_{g_A} + W_{c_F} H_{c_F} = W_{mix_C} H_{mix_C} + W_{c_I} H_{c_I} \pm \int_0^L q_H(x) dx \quad (1)$$

gas energy in + coolant energy in = gas mixture energy out + unvaporized coolant energy out \pm energy losses.

$$W_{mix_C} H_{mix_C} = W_{c_C} H_{c_C} + W_{g_C} H_{g_C} \quad (2)$$

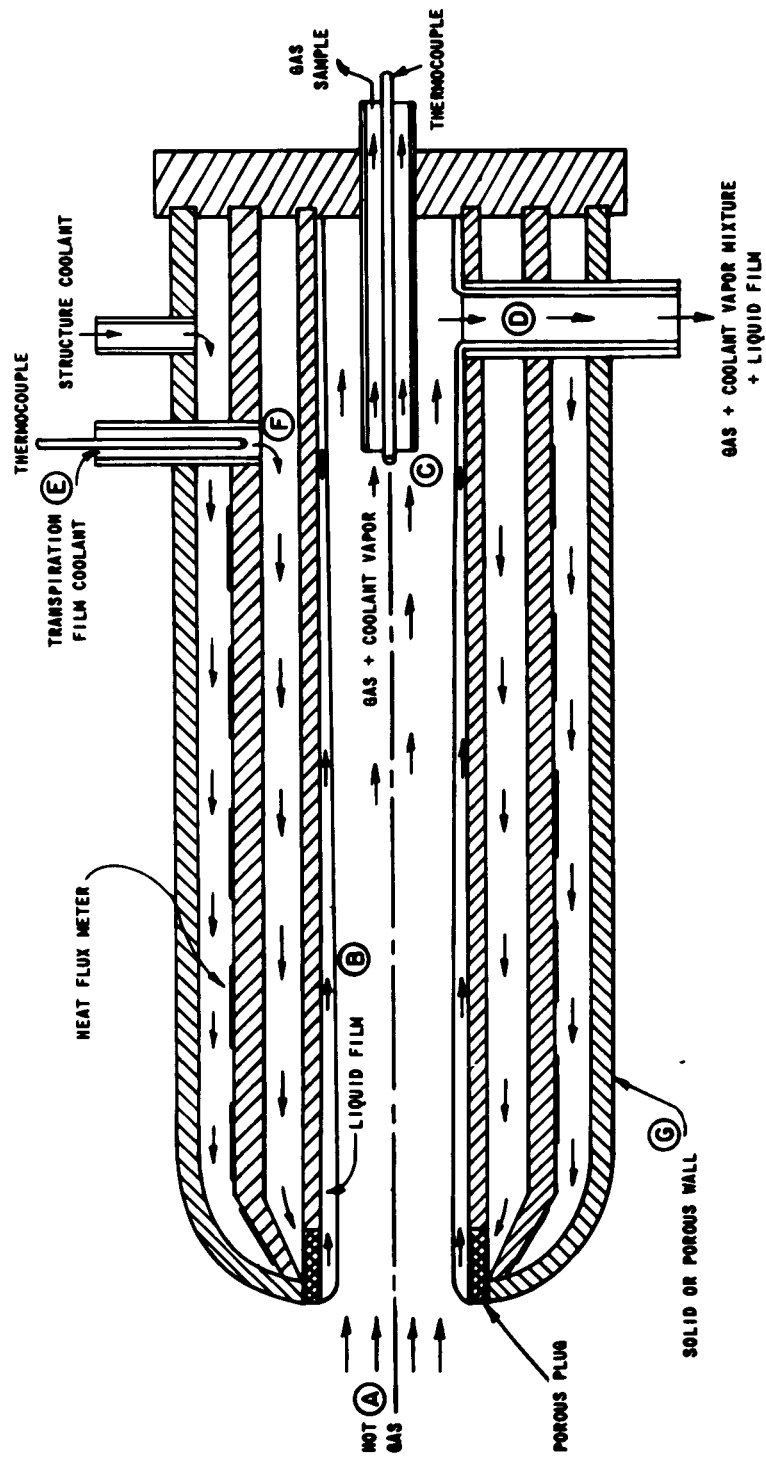


Figure 1 DIAGRAM OF EVAPORATION FILM COOLED ENTHALPY PROBE

Rearranging:

$$H_{gA} = \frac{W_{cC}}{W_{gA}} H_{cC} + \frac{W_{gC}}{W_{gA}} H_{gC} + \frac{W_{cI}}{W_{gA}} H_{cI} - \frac{W_{cF}}{W_{gA}} H_{cF} \quad (1a)$$

$$\pm \frac{1}{W_{gA}} \int_0^L q_H(z) dz$$

$$W_{cF} = W_{cC} + W_{cI} \quad (3)$$

$$H_{gA} = H_{gC} + \frac{W_{cC}}{W_{gA}} (H_{cC} - H_{cF}) + \frac{W_{cI}}{W_{gA}} (H_{cI} - H_{cF}) \pm \frac{1}{W_{gA}} \int_0^L q_H(z) dz \quad (1b)$$

The liquid film thickness required is small and calculations show that, for realistic operating conditions, the average temperature of the liquid film is very close to the vaporization temperature.

$$H_{gA} = H_{gC} + \frac{W_{cC}}{W_{gA}} \left[\int_{T_{cF}}^{T_v} C_{p_{c_{liq}}} (T) dT + \lambda_{vap} + \int_{T_v}^{T_{cC}} C_{p_{c_{vap}}} (T) dT \right] \quad (1c)$$

$$+ \frac{W_{cI}}{W_{gA}} \int_{T_{cF}}^{T_v} C_{p_{c_{liq}}} (T) dT \pm \frac{1}{W_{gA}} \int_0^L q_H(z) dz$$

A mass balance about the gaseous portion of the thermodynamic system yields:

$$W_{cC} + W_{gA} = W_{mixC} \quad (4)$$

$$y_{LC} = \frac{W_{LC}}{W_{mixC}} \quad (5)$$

$$1 - y_{LC} = y_{gC} = \frac{W_{gA}}{W_{mixC}} \quad (5a)$$

$$\frac{W_{LC}}{W_{gA}} = \frac{y_{LC}}{1 - y_{LC}} \quad \frac{W_{CI}}{W_{gA}} = \frac{W_{CF}}{W_{gA}} - \frac{y_{LC}}{1 - y_{LC}} \quad (6)$$

$$H_{gA} = H_{gC} + \frac{y_{LC}}{1 - y_{LC}} \left[\int_{T_{CF}}^{T_v} C_{p_{CLiq}}(T) dT + \lambda_{vap} + \int_{T_v}^{T_{CC}} C_{p_{Cvap}}(T) dT \right] \\ + \left(\frac{W_{CF}}{W_{gA}} - \frac{y_{LC}}{1 - y_{LC}} \right) \int_{T_{CF}}^{T_v} C_{p_{CLiq}}(T) dT \pm \frac{1}{W_{gA}} \int_0^L q_H(x) dx \quad (1d)$$

The above equation is a general operating equation useful for any type of evaporating coolant. Use of enthalpy tables allows simplification:

$$H_{gA} = H_{gC} + \frac{y_{LC}}{1 - y_{LC}} [H_{LC} - H_{CF}] + \left(\frac{W_{CF}}{W_{gA}} - \frac{y_{LC}}{1 - y_{LC}} \right) [H_{CLiqT_v} - H_{CF}] \\ \pm \frac{1}{W_{gA}} \int_0^L q_H(x) dx \quad (1e)$$

Entrance gas enthalpy = exit gas enthalpy + enthalpy loss to vaporized coolant + enthalpy loss to nonvaporized coolant \pm enthalpy loss or gain due to energy sinks or sources.

Equation (1e) may be rearranged to simplify computation:

$$H_{gA} = H_{gC} + \frac{y_{cC}}{1-y_{cC}} \left[H_{cC} - H_{cLiqT_v} \right] + \frac{W_{cF}}{W_{gA}} \left[H_{cLiqT_v} - H_{cF} \right] \pm \frac{1}{W_{gA}} \int_0^L q_H(x) dx \quad (1f)$$

In these equations, the interface temperature at point C (T_{cLiqT_v}) is unknown. This may be evaluated from the following implicit equation derived by considering the heat flux arriving at the liquid gas interface and the mass diffusion leaving in conjunction with Dalton's Law for gas mixtures. Derivation of Equation (7) is given in Appendix B.

$$\frac{\lambda_{c,vap} [y_{ci} - \bar{y}_c]}{\bar{H}_g - H_{gi} + \bar{y}_c (\bar{H}_c - \bar{H}_g) - y_{ci} (H_{ci} - H_{gi})} = \frac{M_g}{M_c} \left(\frac{P_T}{P_{ci}} - 1 \right) \quad (7)$$

P_T , M_g , M_c , \bar{y}_c , \bar{H}_g and \bar{H}_c are known for a particular set of test data.

T_{ci} is selected, thereby automatically setting P_{ci} , λ_{ci} , y_{ci} , H_{gi} and H_{ci} . The correct T_{ci} value is obtained by an iterative solution of Equation (7).

Figure 3 shows interface conditions existing for several measured gas temperatures and compositions for the $N_2 - H_2O$ system at one atmosphere.

Examination of Equation (1d) indicates that for maximum range of operation, the coolant should have a high heat of vaporization and a high heat capacity in the gaseous form. Water has been chosen as the coolant for this study because it meets both requirements and is readily available and containable.

For determination of gas enthalpy by this technique, the following measurements need to be taken:

Temperature of the exit gas stream

Vapor composition of the exit gas stream

Gas flow rate

Transpiration coolant flow rate

Energy loss or gain due to external energy sinks or sources

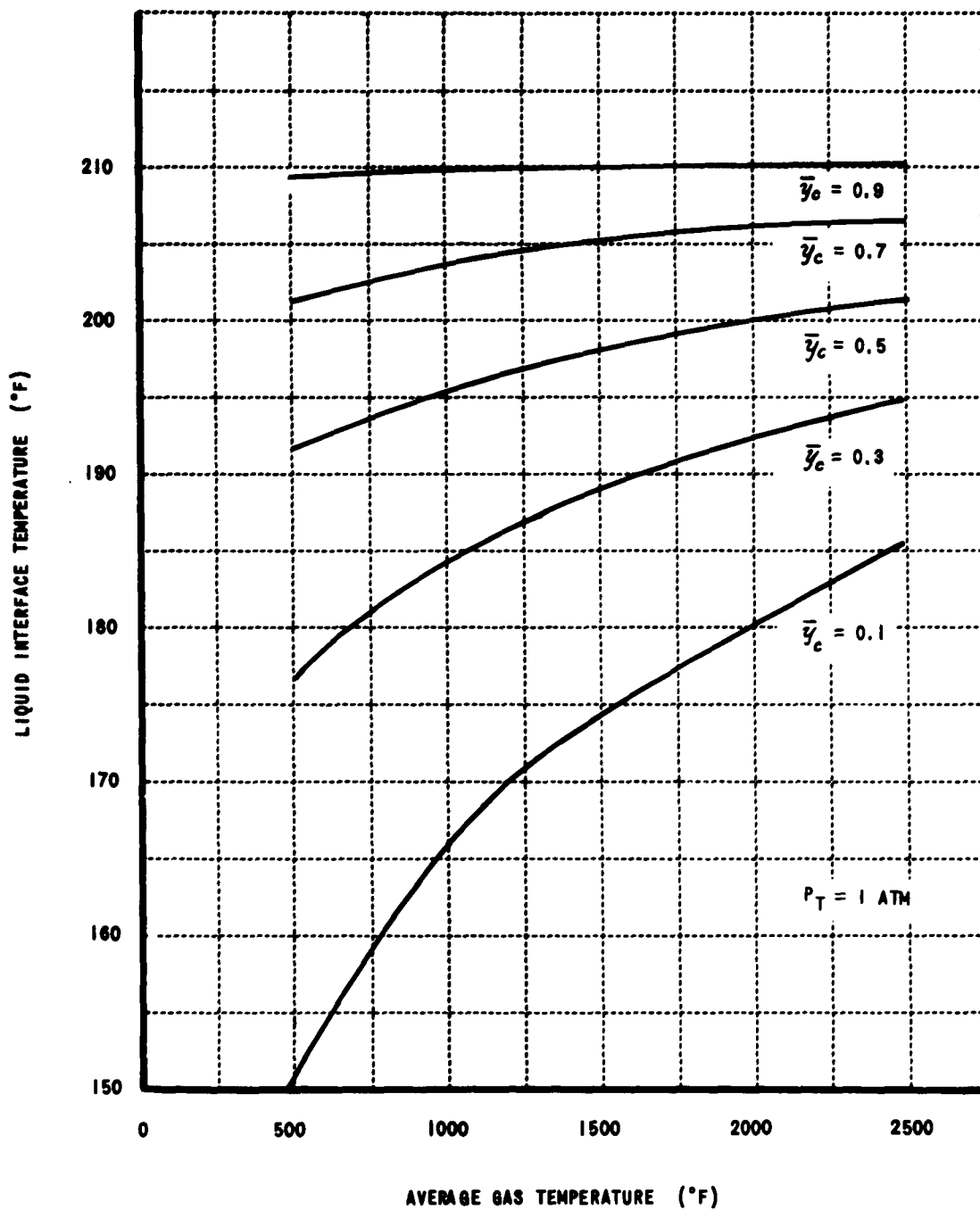


Figure 3 INTERFACE TEMPERATURE FOR N_2 - H_2O SYSTEM

These measurements are straightforward except for those of the gas stream composition and the energy loss or gain. We have found that instrumentation to continuously measure water vapor concentration in the 30 to 90 percent range at elevated temperature ($T \approx 300^\circ\text{F}$) is not available commercially. To make such measurements, we have undertaken development of an instrument for determining the dielectric constant of the gaseous mixture. This instrument is discussed in Section VII. The extraneous energy measurement is accomplished by use of a heat flux meter on the surface of tube *H* as denoted in Figure 2. Figure 4 is a block diagram of auxiliary instrumentation required in support of the evaporating film cooled enthalpy probe.

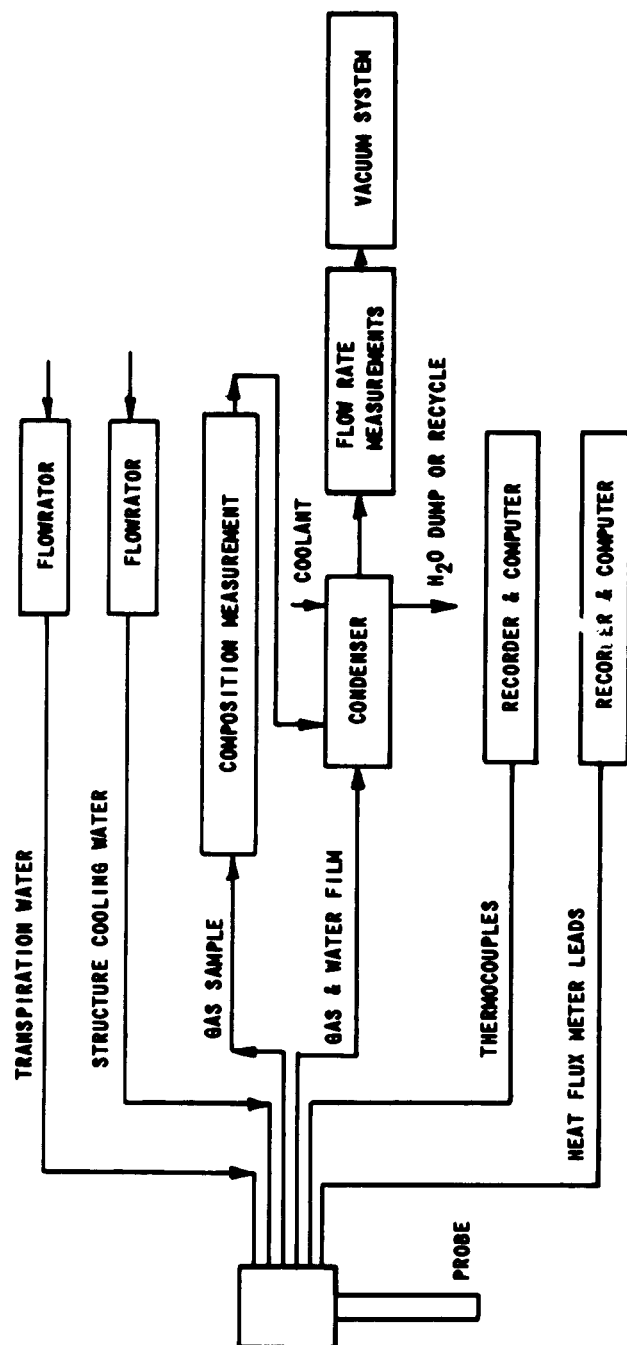


Figure 4 SCHEMATIC BLOCK DIAGRAM OF EVAPORATION FILM
ENTHALPY PROBE AND AUXILIARY EQUIPMENT

IV. EVALUATION OF DESIGN PARAMETERS

Parameters of principle interest in design of the evaporating-film enthalpy probe are probe working length, heat loss to be measured by the heat flux meter, structure coolant flow rate, and pressure drop experienced by the structure coolant flow.

A. OPERATING LENGTH OF THE PROBE

The length of the enthalpy probe is dictated by the requirement that the temperature of the exit gas be low enough that it can be measured by a thermocouple and a gas-sampling probe can be used without thermal degradation of the material. An exit temperature limit of 2500°R is dictated for conveniently usable materials. Axial temperature and composition distributions within the gas-sampling tube were determined by considering the gas sample to be simultaneously developing thermal and hydraulic boundary layers in laminar flow within a solid wall tube. The liquid film of coolant covering the solid surface has been considered to be the gas tube wall, and the heat flux arriving at this wall provides the energy for evaporation of coolant and the energy which escapes through the liquid layer and solid surface to the structural cooling water. The coolant vapor after evaporation provides additional cooling of the core of gas by mixing. In the initial entry region of the gas-sampling tube, the coolant is at its entry temperature. In this region, the heat flux incident upon the interface provides energy to heat the coolant to its vaporization temperature. The liquid film coolant is of the order of 0.001" thick, and calculations show that the temperature gradient through the film is of the order of 1°F ; hence the liquid has been considered to be totally at the vaporization temperature. Figure 5 shows the model used in determination of probe working length. Radiation from the hot gas sample was not included in the heat flux incident upon the interface, and instantaneous mixing of the evaporated vapor with the gas core was assumed, i. e., radial concentration gradients were not included

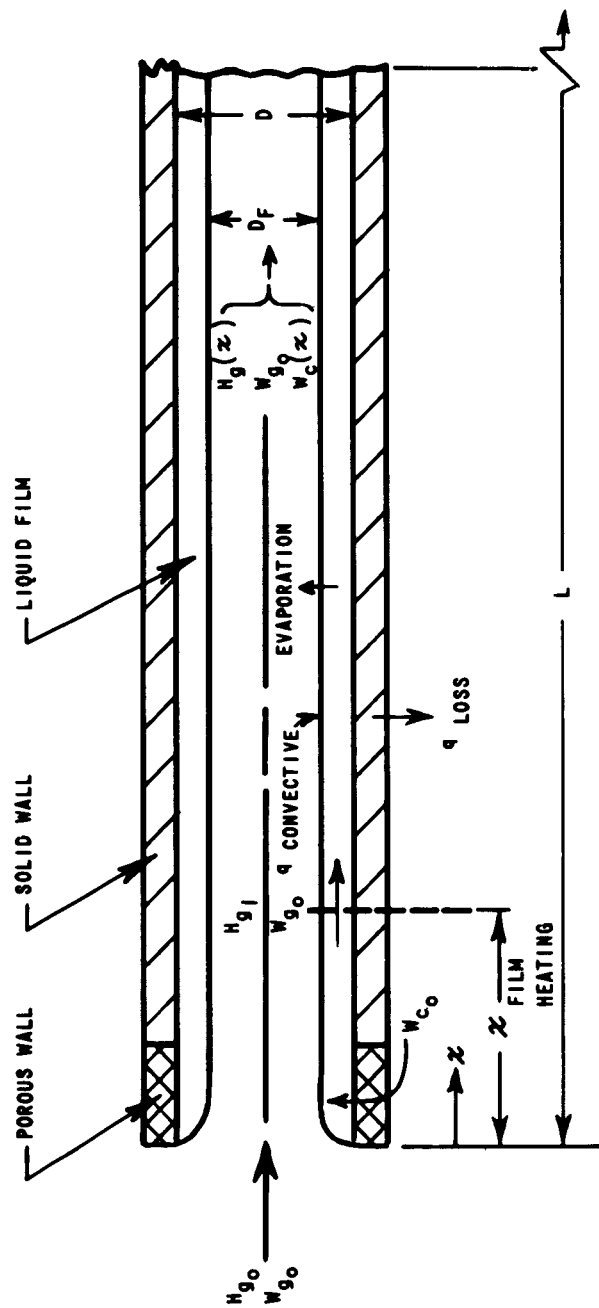


Figure 5 MODEL FOR DETERMINATION OF AXIAL TEMPERATURE AND CONCENTRATION DISTRIBUTION IN GAS-SAMPLING TUBE

in the analysis. Convective heat transfer coefficients were taken from Reference 5; high temperature transport properties of the gases were taken from References 9 and 11, and the mixture properties were approximated by a mass average.

In the coolant film heating region, the change of enthalpy with length is given by:

$$\frac{dH_g}{H_g - H_i} = - \frac{4 Nu(Re_D, Pr, x/D)}{Re_D \cdot Pr} dx \left(\frac{x}{D} \right) \quad (8)$$

$Nu(Re_D, Pr, x/D)$ is taken from Reference 5. Evaporation does not occur in this region; hence, an energy balance directly gives the temperature of the coolant film as a function of length. When the film temperature approaches the vaporization temperature (Equation (7)) evaporation becomes significant. The heat loss from the gas via convective heat flux to the interface surface provides the energy for evaporation of coolant and the energy loss through the liquid film.

$$[W_{g_0} + W_c(x)] \frac{dH_g}{dx} - H_g(x) \frac{dW_c}{dx} = \lambda \frac{dW_c}{dx} + q(x) \quad (9)$$

The enthalpy of the gas mixture at distance x is given by the energy balance:

$$W_{g_0} H_{g_1} = [W_{g_0} + W_c(x)] H_g(x) - W_c(x) H_{c_{liq_1}} - \int_0^x q_{loss}(x) dx \quad (10)$$

The composition of the gas mixture is likewise given by a mass balance:

$$y_g(x) = \frac{W_{g_0}}{W_{g_0} + W_c(x)} \quad (11)$$

Combining Equations (8), (9), (10) and solving by an iterative technique allows evaluation of enthalpy and coolant concentration of the gas stream as a function of working length.

Figure 6 shows the gas stream temperature and composition distribution computed for an experimental model of the instrument. Experimental measurements of the gas temperature and composition were obtained by employing a movable sampling tube which allowed axial traversal of the gas-sampling tube. Experiments were conducted in the experimental probe with gas-sampling tube diameter of 0.060". The movable gas sampler consisted of a 0.033" x .049" stainless steel tube which contained insulated platinum and platinum - 10% rhodium thermocouple lead lines. The experimental data show good agreement with the computed distribution. The fact that inlet gas enthalpy computed from the experimental data was in good agreement with inlet enthalpy measured by a comparison means served as a secondary check of the data. Figures 7 and 8 show the enthalpy and composition distributions computed for two sets of inlet gas conditions in the research model of the enthalpy probe (gas-sampling tube diameter = 0.033"). The inlet conditions considered were low enthalpy-high gas flow (1200 Btu/# - 0.2 #/hr) and high enthalpy-low gas flow (14,000 Btu/# - 0.01 #/hr) which are representative operating limits dictated by use in the ARL vortex stabilized arc. An operating length of 75 diameters reduces the gas temperature to well within the temperature range required for ease of fabrication of available materials and provides considerable safety for probe operation at other inlet conditions.

B. ENERGY LOSS WITHIN PROBE

Energy loss from the gas-sampling tube is computed by considering the structure to be a composite series structure as illustrated in Figure 9. Considering conduction heat transfer, the energy loss per unit length of structure is:

$$\frac{q_{loss}}{\pi} = \frac{2\pi r_1 (T_i - T_{sc})}{r_1 \sum_n \frac{1}{k} \ln \frac{r_{n+1}}{r_n}} \quad (12)$$

The only quantity not based on size of the structure is the thickness of the liquid coolant film. This thickness may be estimated by equating the shear

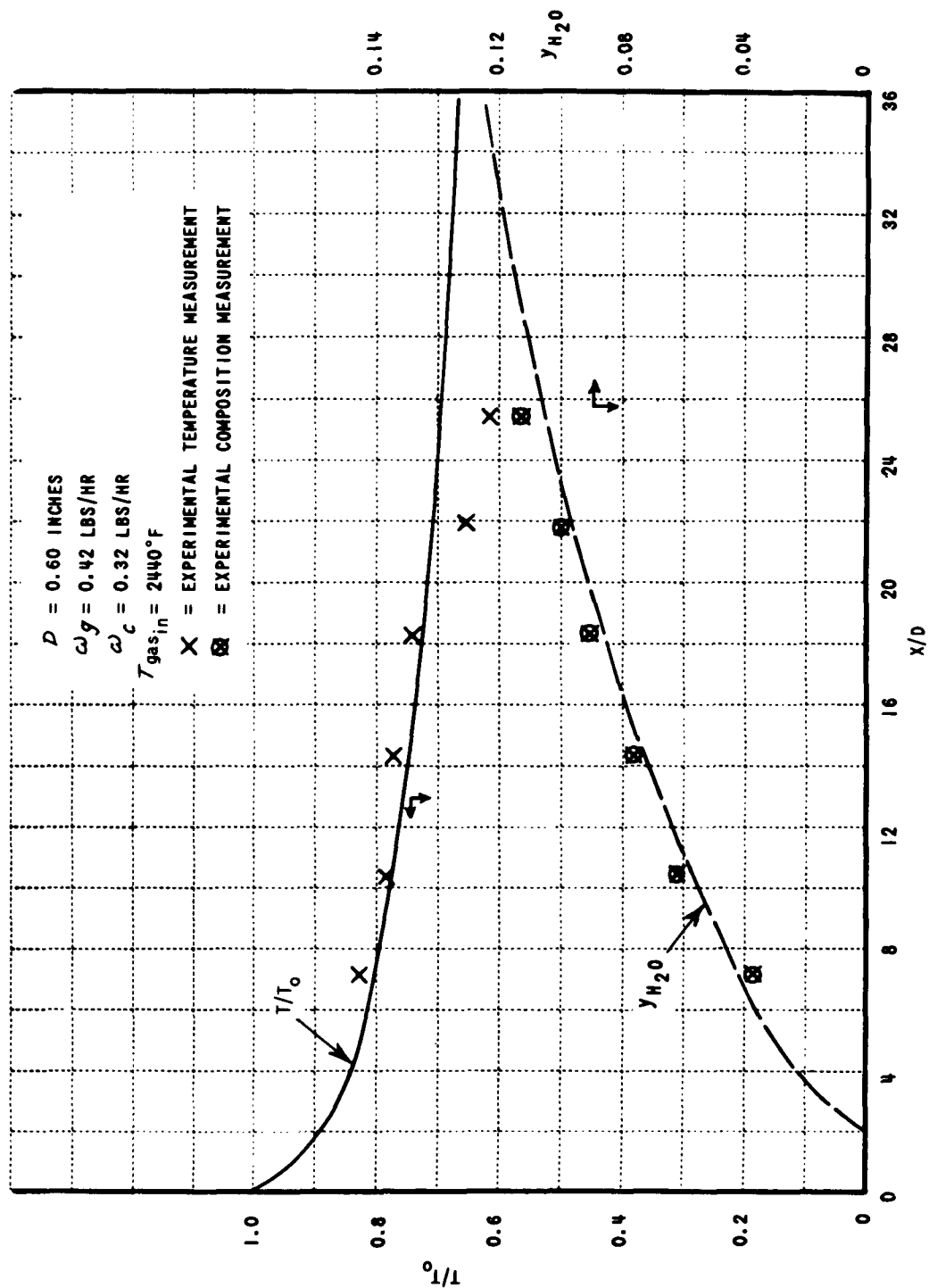


Figure 6 TEMPERATURE AND COMPOSITION VS AXIAL LENGTH FOR EXPERIMENTAL MODEL 2

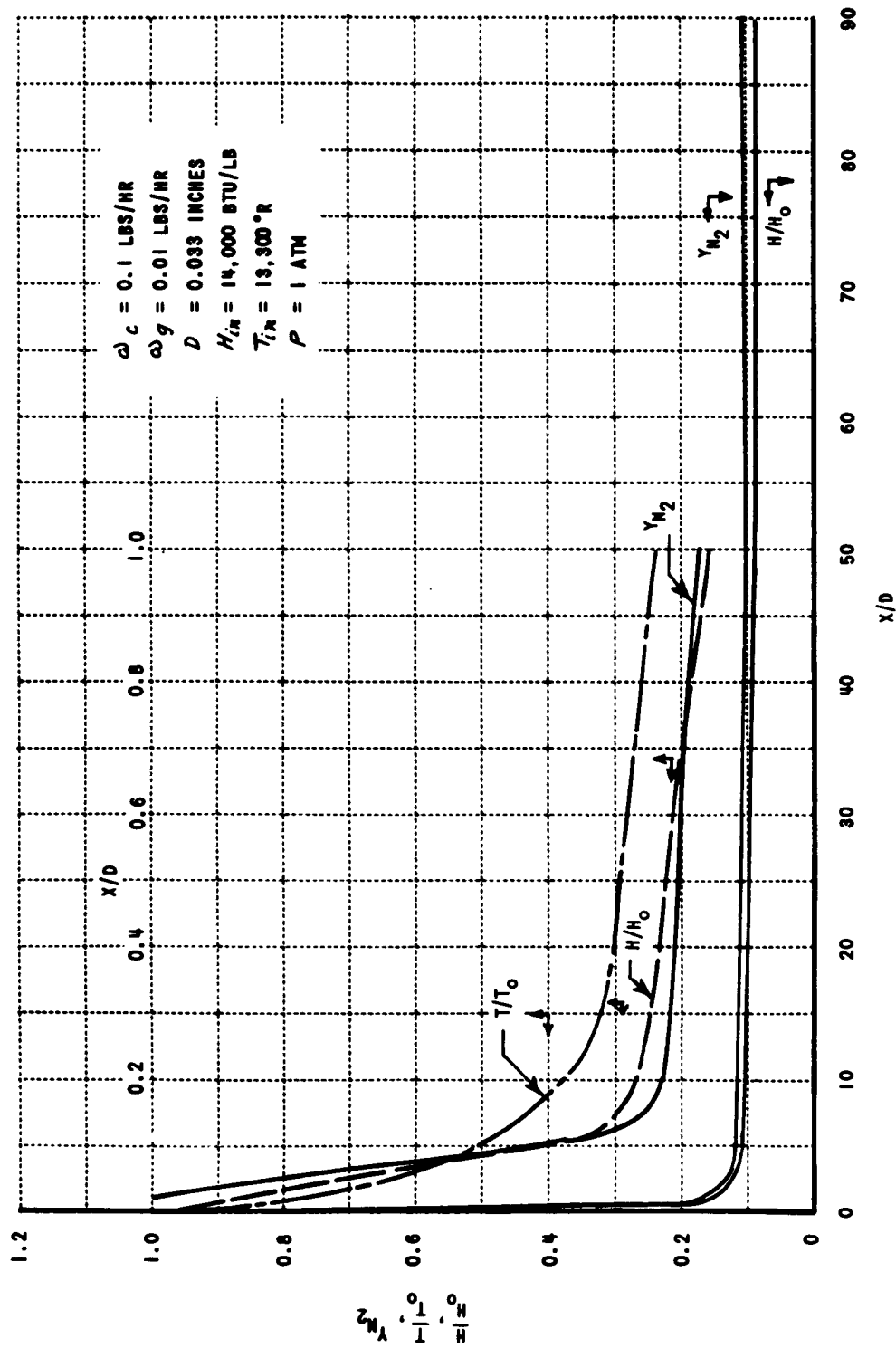


Figure 7 ENTHALPY AND COMPOSITION VS AXIAL LENGTH FOR RESEARCH MODEL

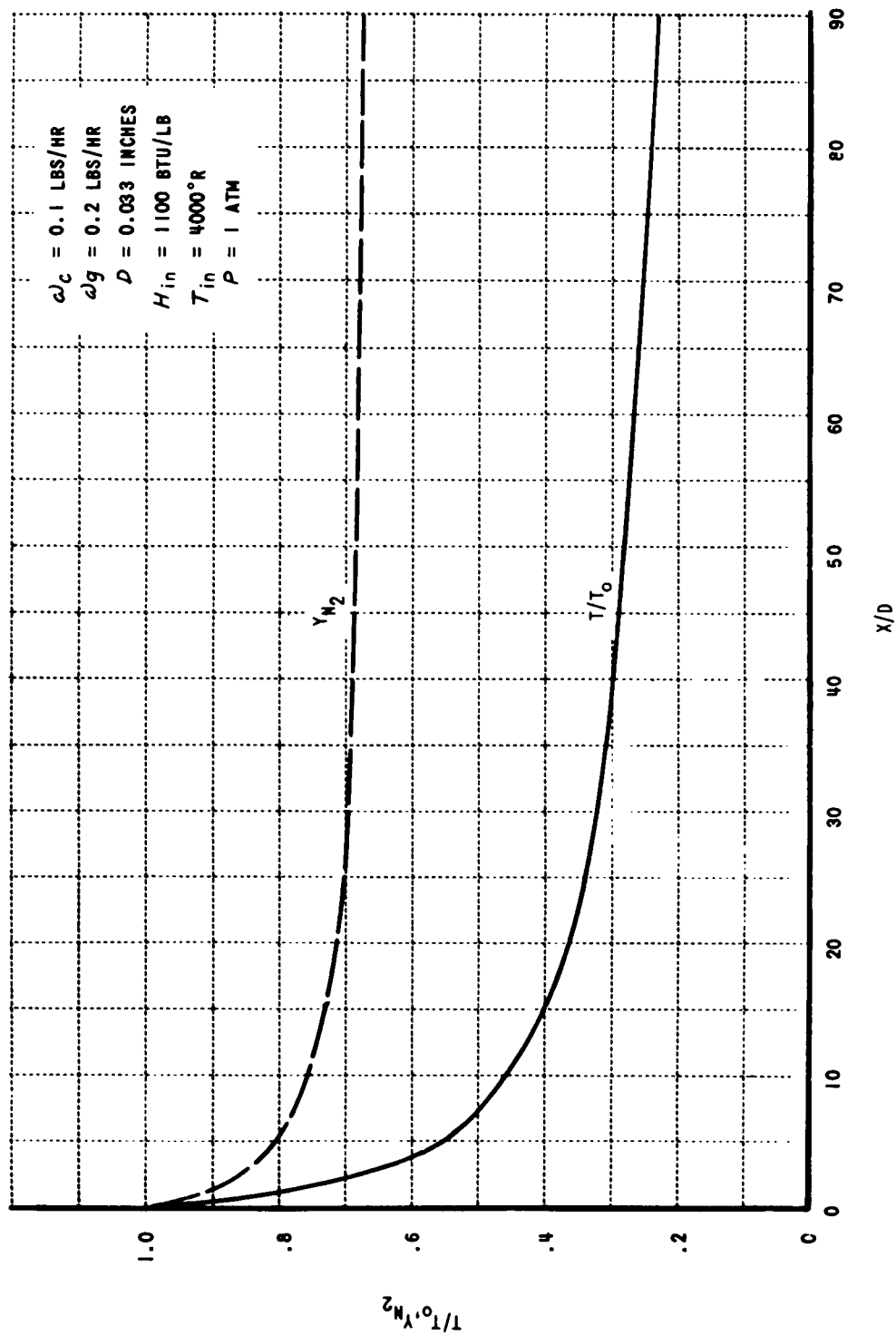


Figure 8 TEMPERATURE AND COMPOSITION VS AXIAL LENGTH FOR RESEARCH MODEL

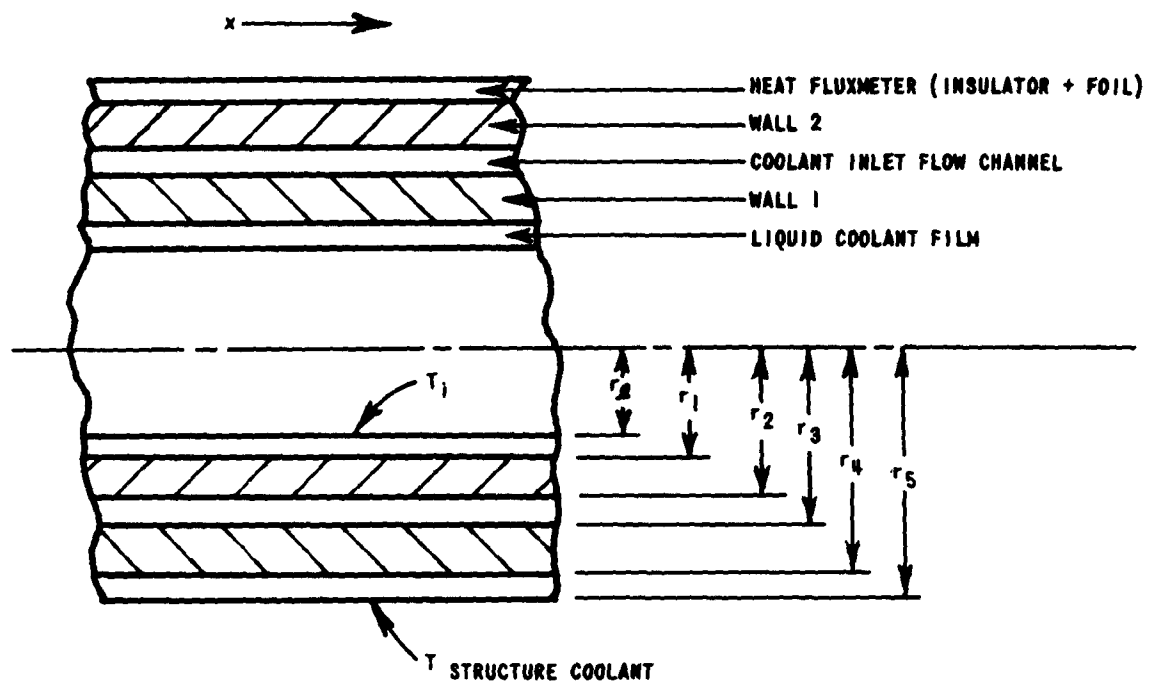


Figure 9 MODEL FOR DETERMINATION OF ENERGY LOSS FROM SAMPLING TUBE

forces at the liquid-gas interface. Use of parabolic velocity profile in the laminar gas flow and a straight-line velocity profile in the liquid film provides:

$$\frac{\delta}{r_i} = \frac{r_L - r_i}{r_i} = \sqrt{\frac{\nu_{liq}}{\nu_g} \cdot \frac{W_{liq}}{W_{go}} \cdot \frac{y_L}{2}} \quad (13)$$

For the research model configuration operating at an average interface temperature of 200 °F and an average structure coolant temperature of 100 °F, the heat loss is 16 Btu/hr. per inch of length. This loss figure may be reduced by operating the structure coolant at a higher temperature. The figure cited is the maximum value which the heat flux meter will be required to detect.

C. STRUCTURE COOLANT FLOW RATE AND PRESSURE DROP

The mass flow rate of the structure coolant is dictated by the need for providing a sufficiently high heat transfer coefficient to insure structural integrity of the instrument. The stagnation heat flux incident upon the probe is computed from Equation (14) below taken from Reference 2. Although this equation has been derived for supersonic flow, it has been shown to be applicable to subsonic plasma flow in Reference 4.

$$\frac{q}{A} = 0.763 Pr^{-0.6} (\rho\mu)_w^{0.9} (\rho\mu)_s^{0.4} \left[1 - (Le^{0.52} - 1) \frac{H_D}{H_S} \right] \left(\frac{du}{dx} \right)^{1/2} (H_S - H_w) \quad (14)$$

The stagnation point gas density has been evaluated from:

$$\frac{P}{P_i} \cdot \frac{\rho_i}{\rho} = \left(\frac{H}{H_i} \right)^{0.615 + 0.040 \log_{10} P/P_i} \quad (15)$$

This equation is discussed in Appendix C. The stagnation heat flux upon the 0.10" hemispherical nose enthalpy probe has been computed for several operating conditions. At an enthalpy level of 14,000 Btu/# the stagnation point heat flux is of the order of 1500 Btu/ft²sec. The structure coolant flow

rate has been computed as a function of stagnation heat flux by use of conventional heat transfer relationships concerning turbulent liquid flow in a tubular annulus. Figure 10 shows the flow rate required to prevent local boiling at the tip of the probe. Figure 11 shows the pressure drop associated with these flow rates traversing the research model of the enthalpy probe.

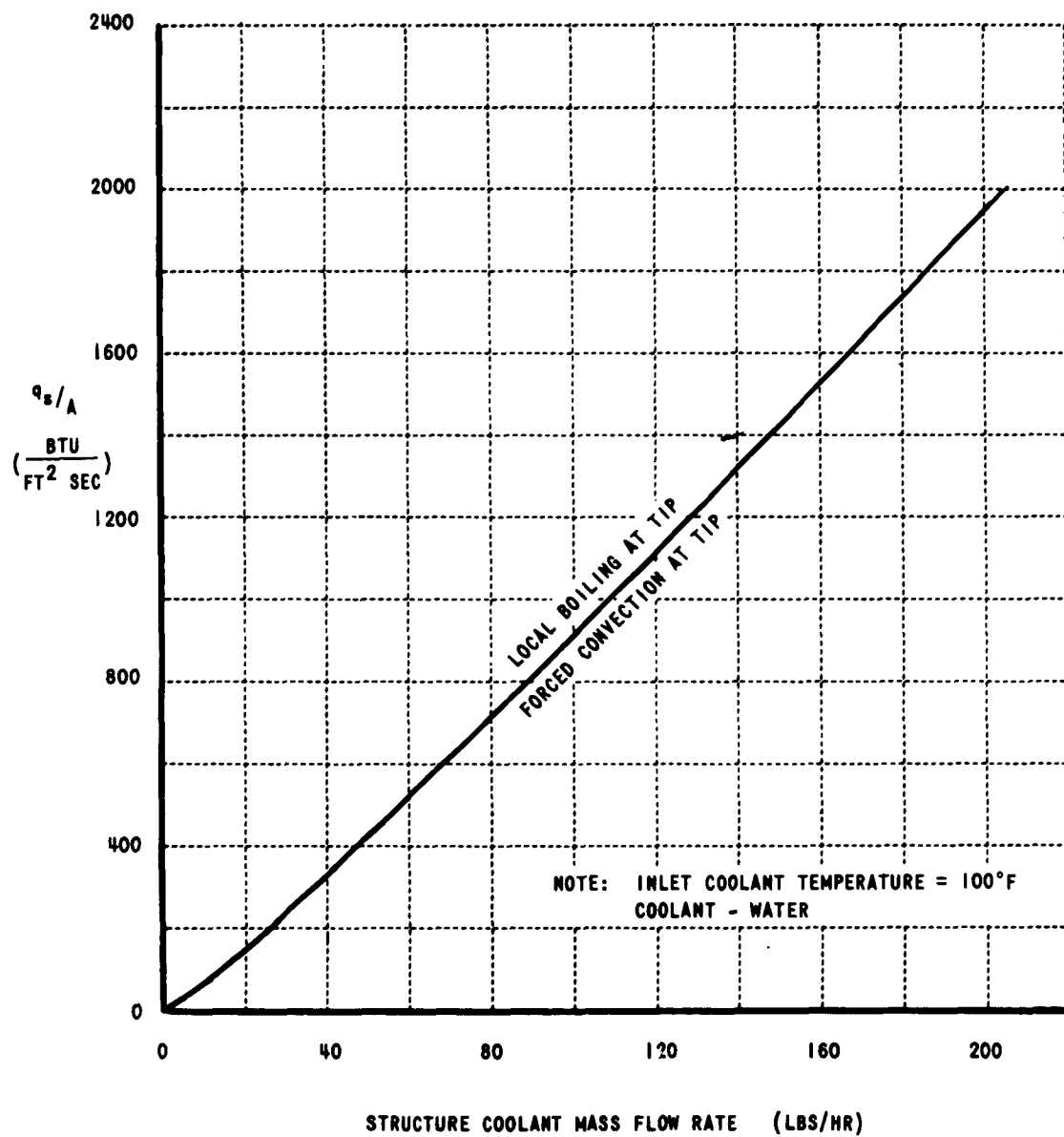


Figure 10 STRUCTURE COOLANT MASS FLOW RATE VS STAGNATION HEAT FLUX

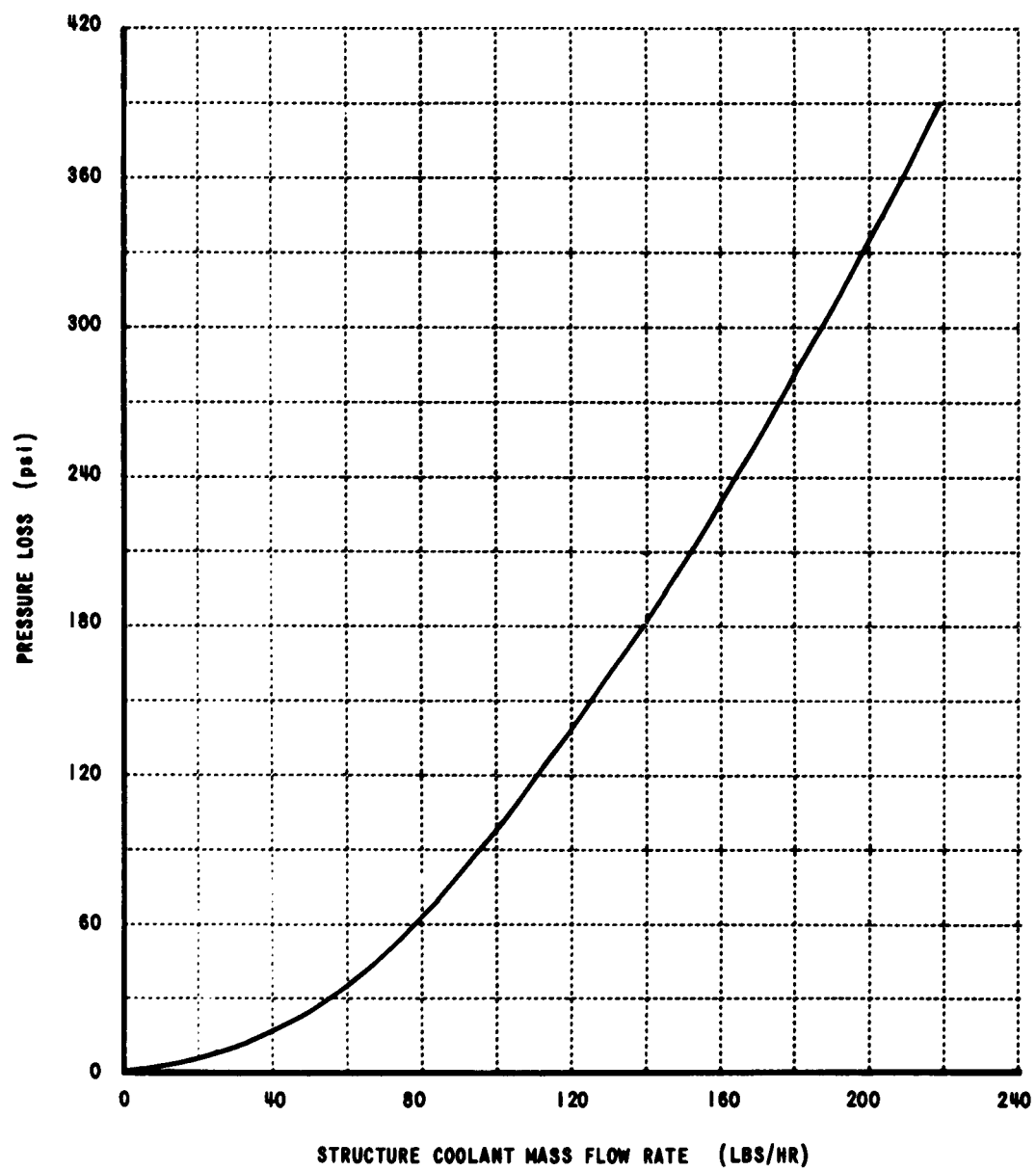


Figure II STRUCTURE COOLANT FLOW RATE VS PRESSURE LOSS

V. ANALYSIS OF ERRORS

Errors in measured enthalpy may occur from two sources, those due to inaccuracies in the component measurements or those due to physical processes occurring which are neglected in the computational procedure. The latter type of error includes radiation heat flux impinging upon the gas sampling tube cavity which causes evaporation of the coolant not associated with heat transfer from the gas sample, and errors in the gas stream composition due to chemical reactions between the nitrogen and the coolant gas. The chemical reaction error may be alleviated by performing a complete quantitative analysis of the exit gas stream and accounting for the enthalpy connected with each component in the exit gas stream in the energy balance; however, it is much more desirable to make only a two-component (gas-coolant vapor) chemical analysis of the exit gas stream since this is more readily adaptable to continuous operation. In the following, the maximum error due to component measurement is computed in addition to the level of error anticipated due to radiation and chemical reaction.

A. ERROR DUE TO COMPONENT MEASUREMENTS

The operating equation written in simplified computational form is:

$$H_{gA} = H_{gC} + \frac{y_{cC}}{1-y_{cC}} \left[H_{cC} - H_{cLi} q_{Tv} \right] + \frac{W_{cF}}{W_{gA}} \left[H_{cLi} q_{Tv} - H_{cF} \right] + \frac{1}{W_{gA}} \int_0^L q_H(x) dx \quad (1f)$$

An analysis of several inlet-gas and coolant conditions, encompassing the full range of instrument operation, indicates that the enthalpy of the inlet gas is divided as follows. The exit-gas enthalpy (first term on right side of Equation (1f) accounts for 10 percent, the enthalpy contribution to evaporation and heating of coolant vapor (second term) accounts for 65 percent, the enthalpy contribution to heating of the liquid coolant (third term) accounts for 7 percent, and the enthalpy contribution to heat loss within the instrument (fourth term)

accounts for the remaining 18 percent. The errors anticipated in the individual component measurements are given in Table 1 below.

TABLE 1
ERRORS ASSOCIATED WITH COMPONENT MEASUREMENTS

<u>Measure- ment</u>	<u>Sensor</u>	<u>Estimated Error</u>	<u>Basis for Error Selection</u>
H_{gC}	Platinum-Platinum 10% Rhodium Thermocouple	$\pm 0.5\%$	Manufacturer's Suggested Error
H_{cC}	Platinum-Platinum 10% Rhodium-Thermocouple	$\pm 0.5\%$	"
H_{cF}	Copper-Constantan Thermocouple	$\pm 1.0\%$	"
W_{cF}	Precision Rotometer	$\pm 1.0\%$	"
W_{gA}	Precision Rotometer	$\pm 1.0\%$	"
H_{cLiqTr}	Evaluated from Equation (7)	$\pm 1.1\%$	Error Analysis of Equation (7)
$\int q(x) dx$	Heat Flux Meter	$\pm 4.0\%$	Calibration
y_{gC}	PVT Measurement	$\pm 2.5\%$	Error Analysis of Equation (21)
	Dielectric Constant	$\pm 1.0\%$	Calibration

The maximum error anticipated from Equation (1f) was computed by standard techniques. For illustrative purposes, the error contribution of the second term of the right side is given below.

$$A = \frac{y_{LC}}{1-y_{LC}} (H_{LC} - H_{LC \text{ liq } T_v}) = \frac{y_{LC}}{1-y_{LC}} H_{LC} - \frac{y_{LC}}{1-y_{LC}} H_{LC \text{ liq } T_v} = A' + A''$$

$$H_{LC} \geq 1100 \frac{\text{Btu}}{\#}$$

$$H_{LC \text{ liq } T_v} \leq 180 \frac{\text{Btu}}{\#}$$
(16)

The weighting factor between A' and A'' is in the ratio 0.837:0.163 in the worst case.

$$A' = \frac{y_{LC}}{1-y_{LC}} H_{LC} = \frac{y_{LC}}{y_{GC}} H_{LC}$$

$$\frac{dA'}{A'} = \frac{dy_{LC}}{y_{LC}} + \frac{dH_{LC}}{H_{LC}} - \frac{dy_{GC}}{y_{GC}}$$

$$dy_{GC} = -dy_{LC} \quad \frac{dy_{LC}}{y_{LC}} = \frac{y_{GC}}{1-y_{GC}} \left(\frac{dy_{GC}}{y_{GC}} \right)$$

From Table 1 the maximum error in A' for a specific gas mixture ($y_g = 0.5$) is $\frac{dA'}{A'} = 0.025 + 0.005 + \frac{0.5}{0.5} (0.025) = 0.055$.

Likewise $\frac{dA''}{A''} = 0.061$

Using the weighting factor»

$$\frac{dA}{A} = 0.837 (0.055) + 0.163 (0.061) = 0.056$$

The second term of Equation (1f) is weighted at 0.65 hence the error in computed enthalpy due to this term is $0.65 (0.056) = 0.037$. Considering the other terms in a similar manner indicates that the maximum error in measured enthalpy is 4.9 percent if the exit-gas composition measurement is made to an accuracy of 2.5 percent. An exit-gas composition measurement of one percent error reduces the maximum computed enthalpy error to 2.9 percent. Figure 12 shows the maximum anticipated error as a function of the measured gas composition. This Figure demonstrates the need for accurate gas composition measurement.

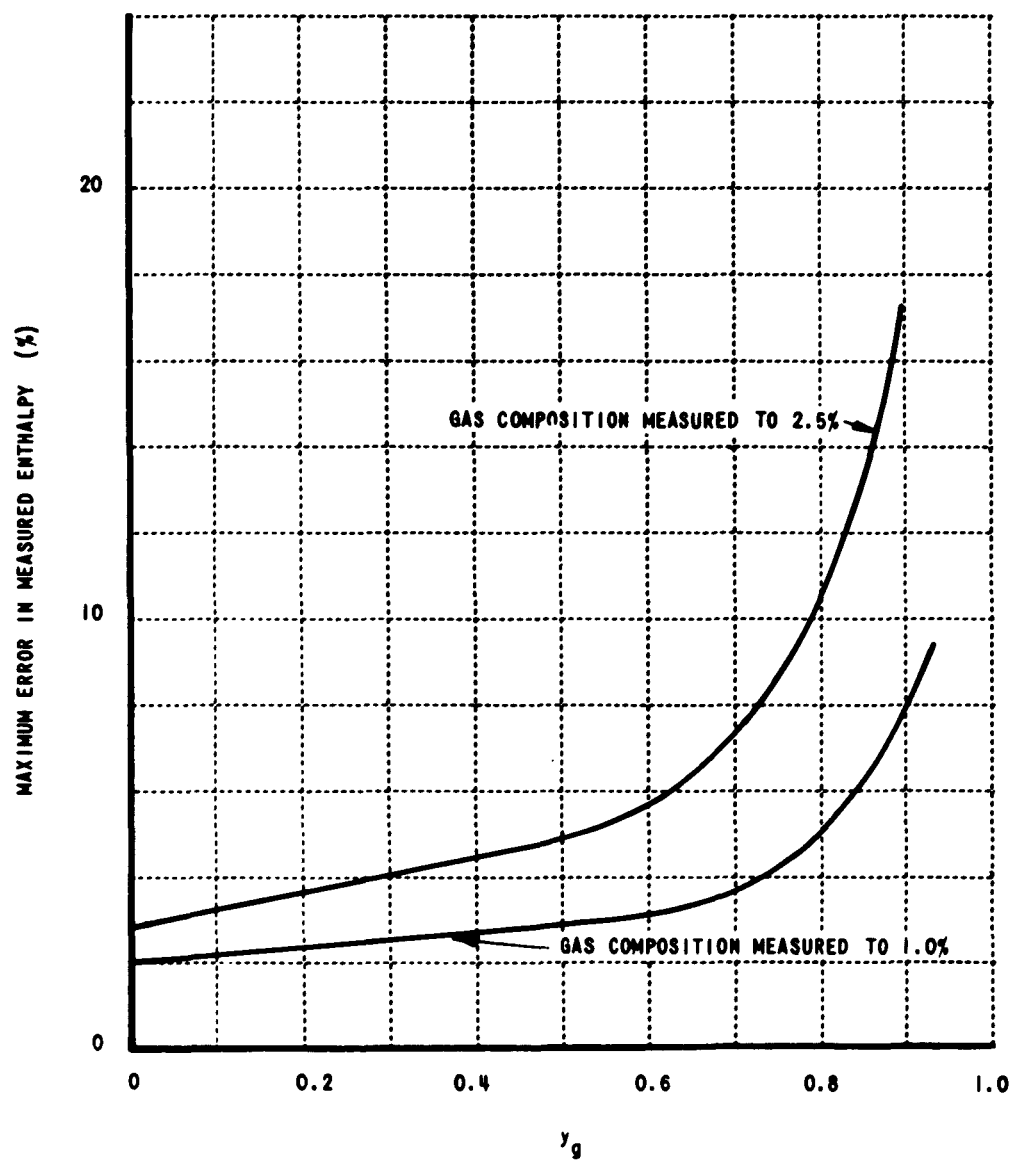


Figure 12 MAXIMUM ERROR IN MEASURED ENTHALPY VS
GAS STREAM COMPOSITION

B. ERROR DUE TO RADIATION INTERCHANGE WITH SURROUNDINGS

The gas-sampling tube acts as a black body absorber of radiant energy entering the sampling tube. This energy is absorbed by the liquid layer surface and hence evaporation of coolant not due to convective or radiation heating from the gas sample occurs. This additional input of energy into the thermodynamic system is a cause of error. Extraneous radiant energy may arrive at the sampling tube from two sources, from high-temperature solid components, such as the electrodes, or from the highly excited gas of the arc. The radiation entering the gas-sampling tube from a hemispherical surface electrode is given by:

$$Q = \sigma \epsilon \pi r^2 \left(\frac{R}{L} \right)^2 \left[T_s^4 - T_p^4 \right] \quad (17)$$

where r is the radius of the gas sampling tube
 R is the radius of the electrode
 L is the distance from the electrode to the probe
 T_s is the surface temperature of the source
 T_p is the probe wall temperature
 ϵ is the emissivity of the electrode material
 σ is the Stefan-Boltzmann radiation constant

Selecting an electrode temperature of 5000 °R and an emissivity value of 1 (worst possible case), the radiation energy entering the probe from this source is one percent of the gas energy carried into the probe by the gas when the distance L is 1.7R. It may be concluded that the radiative energy error from this source is insignificant when the probe is placed more than one source diameter from the source.

Radiation entering the gas-sampling tube from the surrounding sheath of radiating nitrogen is computed by considering the probe to be located at

the center of the base plane of an infinitely long cylinder of gas of diameter d . The equivalent length for this configuration is given as 0.9 by Reference 1 (page 393). Radiation entering the sampling tube is then:

$$Q = \pi r^2 \frac{\epsilon}{L} 0.9 d \sigma T_g^4 \quad (18)$$

ϵ/L for the high temperature nitrogen was taken from Reference 8. Operation at 1 atmosphere and an average temperature of 8000°K with a gas volume diameter of one inch allows 0.46 Btu/hr to enter the gas sampling probe. Under these conditions the gas energy carried into the probe by the gas sample is 140 Btu/hr; therefore, the error from this source of radiant energy is 0.33 percent. It is concluded that use of this instrument in the ARL Vortex Stabilized Arc dictates an error due to stray radiant energy of less than one percent.

C. ERROR DUE TO CHEMICAL REACTION WITH COOLANT VAPOR

Figure 7 indicates that the average temperature of the vapor mixture in the vicinity of gas entrance is sufficiently high that the water vapor will dissociate. This provides a high temperature gas mixture of H, H₂, O, O₂, H₂O, OH, N, and N₂ at a pressure of approximately one atmosphere. The chemical reactions between these gases have been considered for two limiting cases:

- (a) Chemical equilibrium of the gases existing at all times.
- (b) Formation of sideproducts in equilibrium concentration with neglectable rate of reverse reaction.

These two cases provide the limiting conditions upon the amount of reaction product which will be present in the exit gas. The chemical composition of the exit gas was computed for the same initial conditions as the enthalpy distribution computed in Figure 7. The principle chemical reactions considered were the dissociation of water, viz:



and the nitrogen-oxygen reaction:



Equilibrium constant information was taken from Reference 10 for reaction 19 and from References 10 and 13 for reaction 20. Computations were made for a pressure of one atmosphere in all cases. Figure 13 is a plot of the oxygen in the vapor mixture as a function of axial length. The amount of nitrogen used in the nitric oxide reaction under equilibrium conditions is also shown in Figure 13. If chemical equilibrium exists throughout the gas-sampling tube the amount of nitrogen used in chemical reaction products in the exit gas stream is less than one part in ten thousand, which represents essentially zero error in the measured enthalpy. In the other extreme, the maximum amount of side product that can exist in the exit gas is the maximum equilibrium amount formed in traversing the gas-sampling tube. Here, the hypothetical assumption has been made, that none of the nitric oxide formed reverts to component nitrogen and oxygen in the cooler portions of the gas-sampling tube. The maximum amount of nitrogen used in the nitric oxide reaction is 0.18 #mole/#mole of nitrogen in the gas mixture. As the gas mixture cools, the hydrogen and oxygen reassociate such that at temperatures below 4000 °R, all the water is again reassociated. The formation of NO₂ by reaction of the NO with oxygen may be neglected since, in the high temperature region where the concentration of oxygen is high, the reaction equilibrium constant is very small and at low temperatures (2000 °R), where the equilibrium constant is of reasonable magnitude, the concentration of oxygen in the vapor mixture is very small. The reaction of nitrogen with hydrogen to produce ammonia was not considered here because this reaction is known to require high pressure and a catalyst to maintain a reasonable rate of reaction. The cooled gas stream, under the above assumptions which produce maximum amounts of reaction products, is of the following composition.

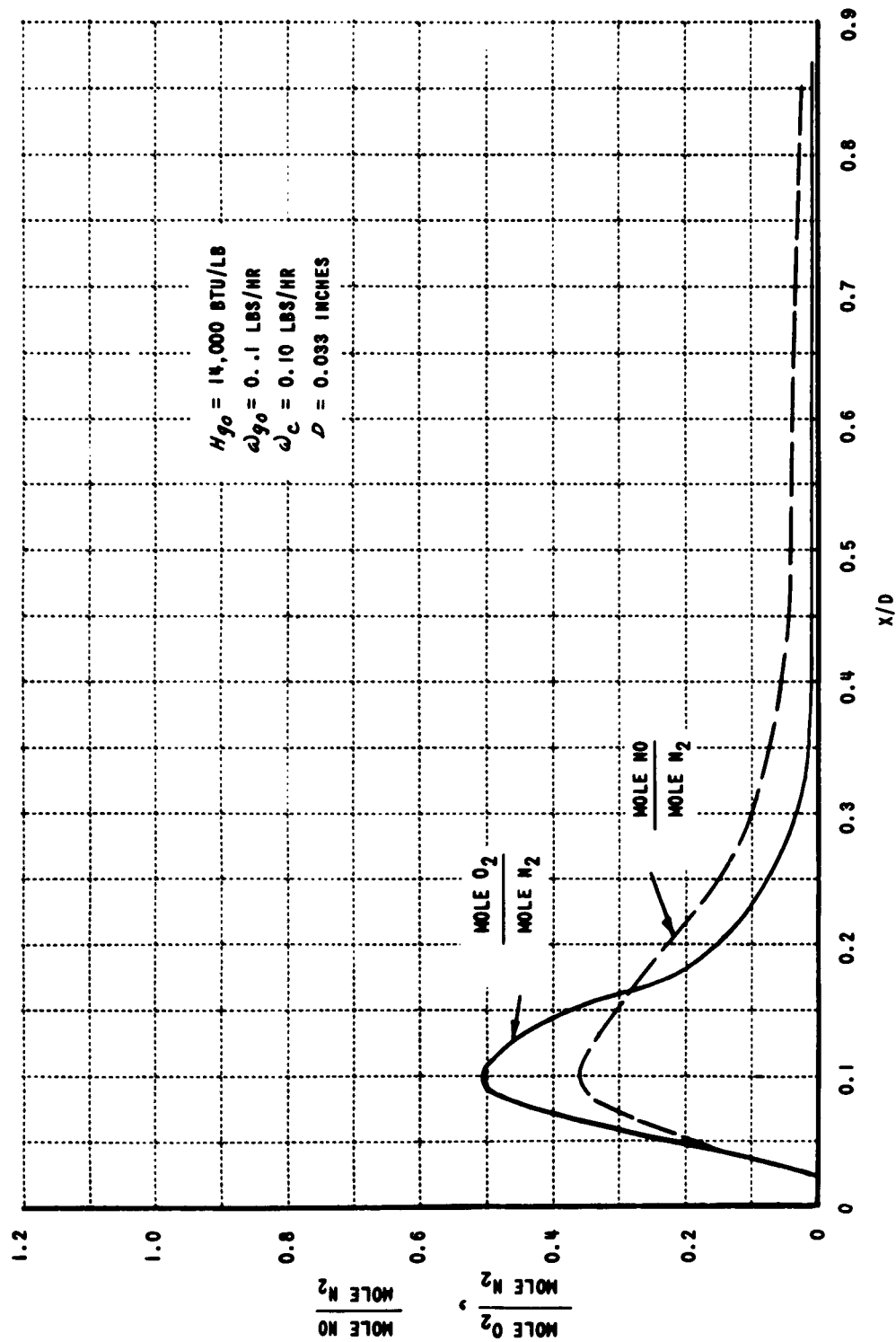


Figure 13 CONCENTRATION OF OXYGEN AND NITRIC OXIDE VS AXIAL LENGTH OF RESEARCH MODEL

<u>Component</u>	<u>Mass Fraction</u>
H ₂ O	0.880
N ₂	0.100
NO	0.019
H ₂	0.001

If chemical reaction had not occurred, the composition would have been 89 percent water vapor and 11 percent nitrogen. The error in measured enthalpy due to neglect of the chemical reaction products is seven percent. Under assumption of maximum product formation by chemical reaction of the sampled gas with the vaporized coolant, the error in the measured enthalpy is seven percent. Due to the severity of assumptions made, it is believed that the actual error will be considerably less than this maximum value. If a complete quantitative analysis of the gas stream is made, this error can be avoided.

VI. EXPERIMENTAL PROGRAM

In the course of this program three experimental models of the evaporating film calorimetric enthalpy probe have been constructed. On the basis of information gained from these models, a research model of the instrument has been fabricated. The experimental models were built to yield information about this basic technique of calorimetric enthalpy measurement, and minimum size was not considered as a principal criterion. The research model, which is to be used in an arc, was miniaturized and has an outside diameter of 0.10".

A. EXPERIMENTAL MODELS

The first experimental model has the following dimensions: O. D. = 0.185", gas sampling tube I. D. = 0.020", $L = 2.0$ ". This instrument is shown in Figure 14. The coolant film is formed by 20 - 0.010" holes in the inside tube spaced equally over the first inch of length of the gas sampling tube. The instrument is fabricated of stainless steel and brass. The structure of the instrument is maintained at low temperature by forced convection cooling. Forced convection cooling was chosen as the thermal protection mechanism for the present models since it does not contaminate the gas stream and requires less control. In the future, when yet smaller size and higher heat flux are primary objectives, another type of thermal protection system will be required. Evaporative film cooling of the entire structural surface offers an attractive possibility of meeting both objectives.

The second experimental model fabricated was made larger in order that information concerning axial temperature and composition distributions within the gas-sampling tube could be obtained. This model is two inches long, has an O. D of 0.312", and a gas sampling tube I. D. of 0.070". Initially, the coolant film was formed at 10 - 0.0135" holes equally spaced over the first inch of the gas-sampling tube. In a modified version of this model, the 0.070" tube was covered with a 0.060" I. D. tube and the coolant film was formed by use of a 0.20" length of 0.003" screen at the tip of the probe. Figure 15, a drawing of experimental model 2, shows the general type of probe configuration and construction used in the experimental models.

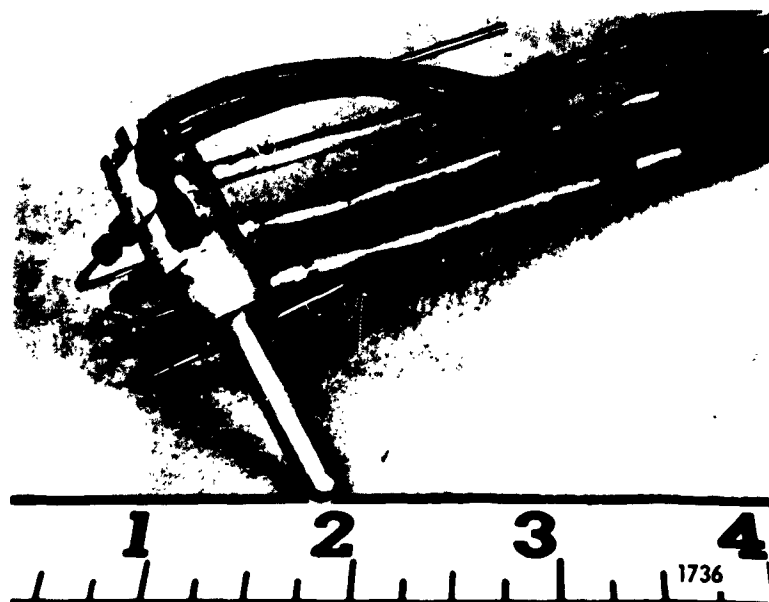


Figure 14 PHOTOGRAPH OF EXPERIMENTAL MODEL I

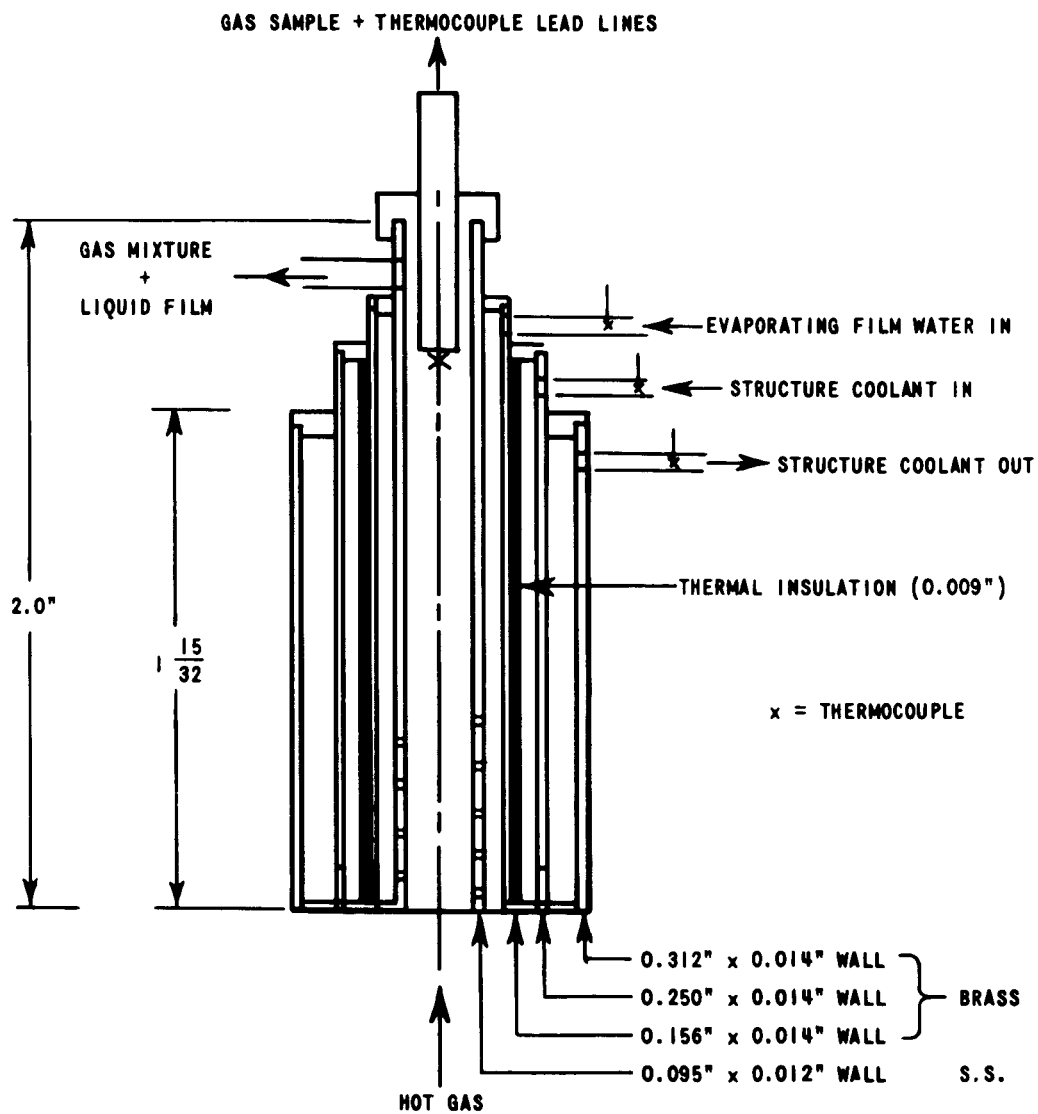


Figure 15 ASSEMBLY DRAWING OF EXPERIMENTAL MODEL 2

B. RESEARCH MODEL

The research model of the enthalpy probe has the dimensions O. D. = 0.105", gas sampling tube I. D. = 0.033", and length = 2.75". The probe is encased in a forced convection cooled strut designed for use in the ARL Vortex Stabilized Arc Facility. The strut has an outside diameter of 0.375" and a working length of 7 inches which allows traversal of a 3 1/2" diameter gas stream. Figure 16 shows the research model itself and the research model encased in the strut.

Figure 17 shows the fabrication details of the research model. The fabrication materials are mainly stainless steel and brass. The evaporating film is formed by 60 holes of 0.004" mean diameter (5 rows of 12 holes of each row) placed over the first 0.060" of the gas sampling tube. A 0.312" strip of 0.002" platinum sheet containing three 180° twists has been placed at the exit end of the gas sampling tube to induce mixing of the exit gas and coolant vapor to insure that the temperature and gas sample taken at exit are representative average values. The gas sampling tube and exit gas thermocouple (platinum-platinum 10% rhodium) are brought through the strut coaxially with the gas exit tube. The gas exit tube has been provided with a heater to prevent condensation of water vapor from the gas mixture. A copper-constantan thermocouple soldered to the gas tube surface allows the wall temperature to be monitored.

The structure of the research model is cooled by forced convection of water in a 0.010" annulus between the heat flux meter surface and the outside wall of the probe. The structure coolant flows from the afterbody to the tip in one half of the annulus, reverses direction at the tip, and flows from the tip to the afterbody in the other half of the annulus. This flow pattern is maintained by two 0.010" copper wires placed in the structure coolant annulus as shown in Section A-A of Fig. 17. The open area for flow reversal is shown in the tip detail of Fig. 17.

Heat losses through the evaporating coolant film to the structure coolant are measured by a heat flux meter placed on the inside surface of the structure coolant channel. The heat flux is obtained by measuring the average temperature differential across a thickness of electrical and thermal insulating material.

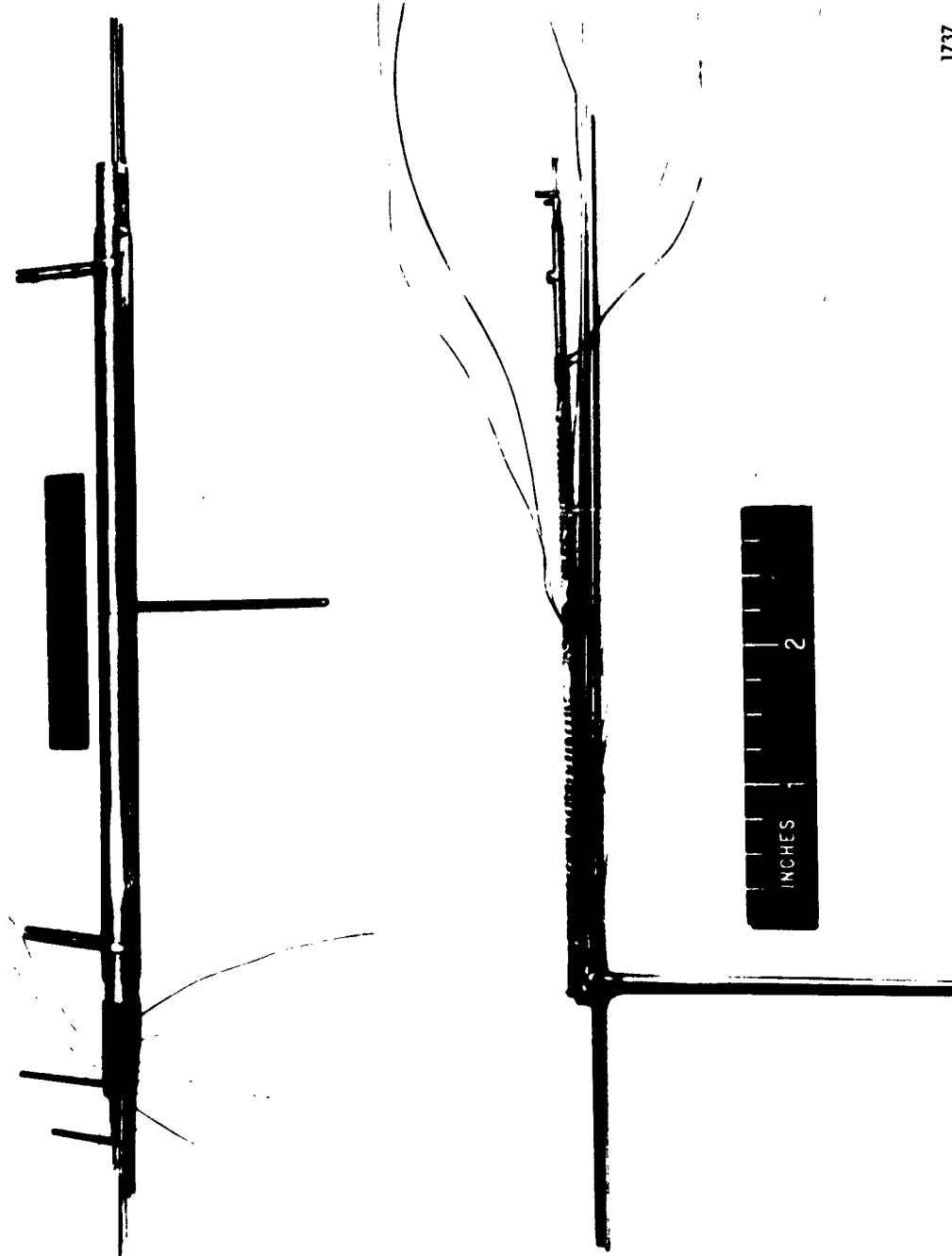


Figure 16 PHOTOGRAPH OF RESEARCH MODEL

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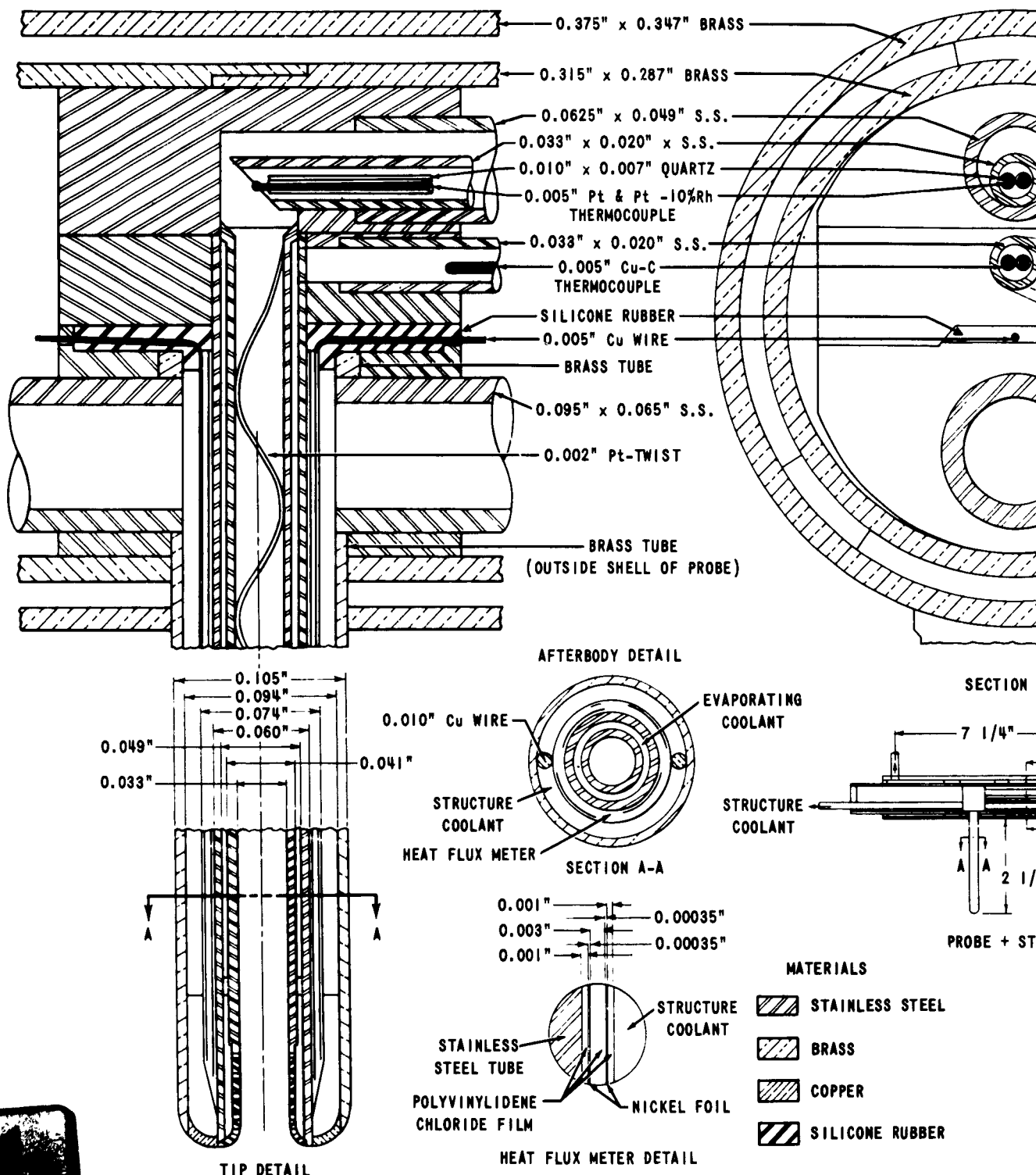


Figure 17 ASSEMBLY DRAWING OF RESEARCH MODEL

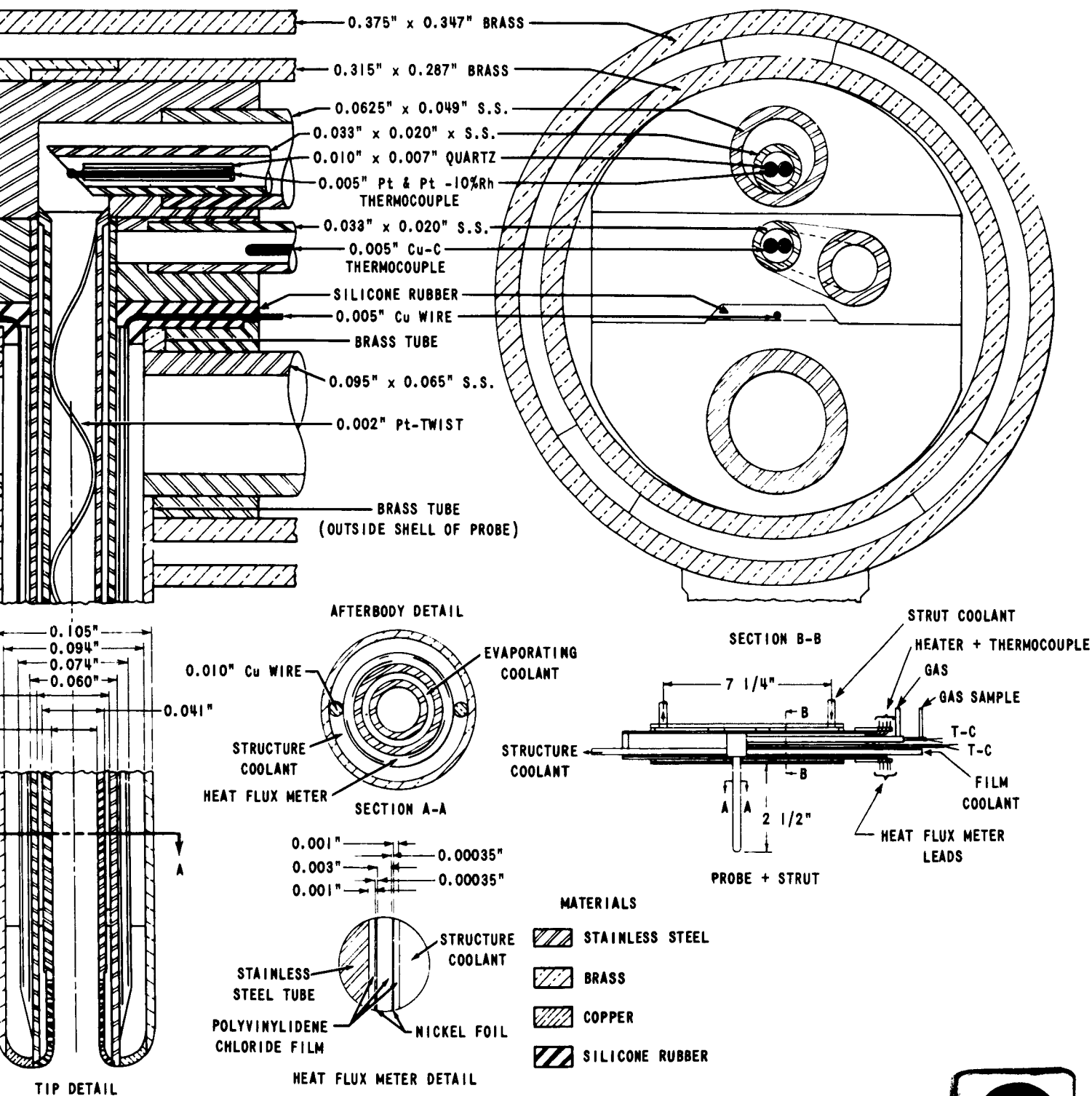


Figure 17 ASSEMBLY DRAWING OF RESEARCH MODEL

Since an average temperature value is desired at each sensor location, resistance thermoelements have been employed as the sensors. The resistance element is nickel foil of 0.00035" thickness. The insulating material is polyvinylidene chloride film and lacquer. The nickel foils are placed in a "U" shape at two distances from the inner structural coolant wall. The closed end of the "U" lies at the tip of the probe and the lead lines are brought from the probe afterbody by copper wire. The heat flux meter detail is shown in Fig. 17. Resistance of the foil elements is measured by a Wheatstone Bridge Circuit and a light beam galvanometer. At 80°F the resistance of the elements is:

$$A: \quad R_A = 1.3662 \, \Omega$$

$$B: \quad R_B = 1.5849 \, \Omega$$

The heat flux meter has been calibrated by measuring the temperature differential of the structure coolant water when the gas flow through the probe is pulsed. This calibration technique is analogous to the continuous instrument calibration used in previous calorimetric enthalpy probes (Ref. 3). Heat loss to the structure coolant is given by:

$$\int_0^L q_N(x) dx = 209.6 [R_A - R_B + 0.2187]$$

The temperature of the entering evaporating film coolant is measured by a copper-constantan thermocouple at the coolant's entry into the probe afterbody. The probe afterbody is fabricated of stainless steel and is made in three parts to facilitate assembly. The parts are sealed with silicone rubber and held together by a press fit within the inner strut tube. Solder joints are used throughout to prevent leakage.

C. EXPERIMENTAL TEST APPARATUS

Experimental enthalpy determinations utilizing these instruments have been made using a laboratory gas heater in which nitrogen is heated by passing through the walls of a porous hollow graphite cylinder. The cylinder is resistance heated by a D. C. power supply. This heater produces a gas temperature of 4500 °R and a heat flux of the order of 300 Btu/ft² sec.

The philosophy of the test program has been to evaluate the accuracy of the instrument at gas stream temperatures which can readily be measured by other more conventional techniques, yet be high enough to give a meaningful test of the evaporation technique of enthalpy measurement. Testing has been done between temperatures of 2200 and 4300 °R. Gas temperatures below 3500 °R have been measured by platinum-platinum 10% rhodium thermocouples which have been radiation shielded and account has been taken of non-total stagnation conditions at the thermocouple. Gas enthalpy at temperatures above 3500 °R has been measured directly by a calorimetric enthalpy probe of the on-off type described in the Introduction (Reference 3). For purposes of this program, an enthalpy probe of the on-off type with an outside diameter of 0.10" was fabricated. This probe contained all instrumentation in the afterbody which, of necessity, increases response time of the instrument; however, this was not a drawback for its intended use. This enthalpy probe was checked for accuracy at gas temperatures between 2300 and 3300 °R and showed an average deviation of 1.5 percent from the enthalpy corresponding to the gas temperature measured by the thermocouple system described above.

Experimental enthalpy determinations were made only after the gas heater had reached a steady state operation. The gas heater has a characteristic of slight rise in gas temperature with time when in steady operation. Calibrations showed this to be a linear rise; hence, the temperature or the enthalpy of the gas stream was determined before and after each enthalpy determination was made with the test instrument. A linear interpolation of the gas temperature data served to give the gas temperature at the exact time the test enthalpy determination was made.

The experimental test apparatus used in enthalpy determination tests is shown in block form in Figure 18. Gas is drawn through the enthalpy probe by a vacuum system. The evaporating coolant water is supplied by a calibrated burette maintained at constant pressure head by a liquid supply system. The coolant flow rate is determined by stopping the liquid supply and measuring the time required for 1 cc to flow into the system. The gas flow rate and the structure coolant flow rate are determined by calibrated rotameters. The water vapor in the gas mixture is condensed, and the gas is dried before the flow rate measurement is made. Thermocouples placed in the inlet and exit structure coolant lines allow evaluation of the energy loss from the gas-sampling tube of the experimental models by the technique of pulsing the gas flow through the tube. Due to lack of commercially available instrumentation to provide a gas composition measurement, we have concurrently with the development of the enthalpy probe developed an instrumentation technique for continuous measurement of the gas stream composition. Because of this lack of instrumentation at the time of testing, the gas composition was determined by measuring the pressure change, in a flask of calibrated volume, due to condensation of the water from the vapor mixture. The gas-sampling flask and all lines connecting the flask and the probe system are thermally insulated and provided with individually controlled heaters in order that the whole system can be maintained at uniform temperature as determined by the eight thermocouples. Before an enthalpy determination test is made, the sampling tube is dried, heated and evacuated. The whole sampling system is heated and allowed to come to an equilibrium temperature T_1 of the order of 700 °R. When equilibrium is established the flask is sealed and the initial pressure P_1 is recorded. During the test, vapor mixture is pulled through the sampling sting and a portion of this gas is allowed to flow into the sampling flask. The flask is again sealed. After the test, the sampling system is allowed to reach equilibrium and the pressure, P_2 , and temperature, T_2 , (≈ 700 °R) are recorded. The entire sampling system is cooled to a temperature of approximately 60 °F and at equilibrium the pressure, P_3 , and temperature, T_3 , are again recorded.

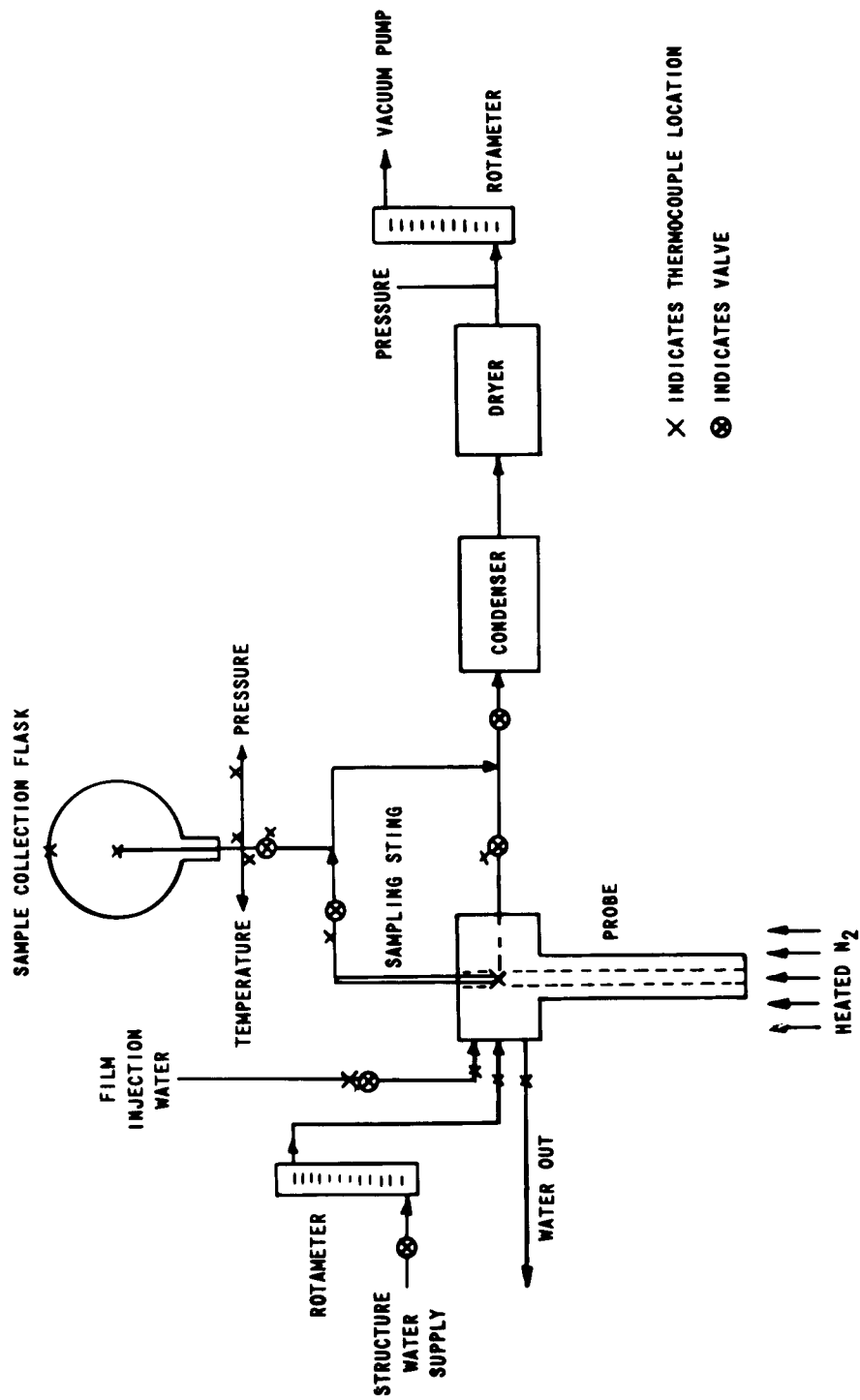


Figure 18 EXPERIMENTAL TEST APPARATUS

The mole fraction of nitrogen in the gas sample is determined by applying the ideal gas law and accounting for the volume change of the system due to changing pressure level in the manometer.

$$Y_{N_2} = \frac{\frac{P_3}{T_3} [0.450 + 0.00285 (30.00 - P_3)] - \frac{P_1}{T_1} [0.450 + 0.00285 (30.00 - P_1)]}{\frac{P_2}{T_2} [0.450 + 0.00285 (30.00 - P_2)] - \frac{P_1}{T_1} [0.450 + 0.00285 (30.00 - P_1)]} \quad (21)$$

The heat flux incident upon the enthalpy probe is obtained by measuring the transient temperature rise of a copper disk of known size, weight, and initial temperature when exposed to the high temperature gas stream. The back face of the copper disk is thermally insulated to prevent rearward heat loss.

D. EXPERIMENTAL TEST RESULTS

Enthalpy determinations have been made between gas temperatures of 2200 and 4300 °R, utilizing water as the film coolant. The test data are tabulated in Table 2 and plotted in Figure 19. These data shown an average deviation 2.3 percent between the enthalpy measured by the evaporating film calorimetric enthalpy probe and the enthalpy as determined by the comparison method. The maximum deviation obtained was 6.0 percent. Maximum heat flux encountered in the testing was 270 Btu/ft² sec.

Preliminary test data obtained with the research model indicate an average deviation of 3.75 percent with a maximum deviation of 6.0 percent. Testing and analysis of the research model will continue.

Figure 20 shows enthalpy of the component gas streams as a function of temperature. Data are taken from References 6, 7, and 9.

Table 2
ENTHALPY DETERMINATION TEST DATA

PROBE	T_{gas} °R	H_{gas} Btu/lb mole	W_g #/hr.	W_c #/hr.	T_{exit} °R	Y_c exit #H ₂ O/#mix	H_{probe} Btu/lb mole	$100 H_{probe}$ H_{gas} %
E-0.070	2635	19,650	0.805	0.70	2222	0.023	20,080	101.8
"	2470	18,350	0.86	0.75	2021	0.030	17,950	98.5
"	2270	16,700	0.87	0.73	2054	0.008	16,470	98.8
"	2750	20,580	0.89	0.78	2206	0.062	19,884	97.0
"	2890	21,800	0.84	0.75	2253	0.090	22,740	104.0
"	2897	21,900	0.86	0.75	2013	0.106	21,815	99.6
"	2980	22,600	0.84	0.71	2040	0.131	23,580	104.0
"	3145	24,000	0.84	0.73	2180	0.090	23,010	96.2
"	3274	25,050	0.84	0.75	2106	0.138	25,060	100.0
E-0.060	3068	23,300	0.65	0.98	1604	0.145	23,750	102.0
"	2979	22,590	0.67	0.87	1580	0.150	23,040	102.1
"	2978	22,590	0.67	0.78	1596	0.170	23,720	105.0
"	3000	22,760	0.67	0.87	1613	0.150	23,300	102.6
"	2147	15,750	0.79	0.98	1315	0.050	15,710	99.9
"	3534	27,300	0.59	0.78	1720	0.185	26,633	97.6
"	3880	30,275	0.54	1.12	1798	0.202	31,600	104.5
"	4260	33,570	0.56	1.21	1799	0.240	33,400	99.7
E-0.060*	2867	21,650	0.38	0.26	2385	0.037	21,644	100.0
" "	2899	21,919	0.40	0.33	2277	0.064	23,200	105.0
" "	2860	21,580	0.45	0.31	2222	0.077	21,400	99.0
" "	2905	21,960	0.48	0.25	2174	0.091	22,470	102.5
" "	2905	21,960	0.48	0.37	1900	0.102	21,840	99.5
" "	2905	21,960	0.41	0.37	1795	0.114	21,220	97.0
" "	2950	22,330	0.37	0.33	1590	0.178	23,880	106.0
R-0.033	2280	16,788	0.21	1.13	684	0.095	15,700	94.0
"	2270	16,700	0.18	1.13	690	0.066	15,630	94.0
"	2280	16,788	0.18	1.10	675	0.100	17,150	102.0
"	2917	22,020	0.13	0.99	754	0.075	21,750	96.5

*AXIAL TEMPERATURE AND CONCENTRATION DETERMINATION TESTS

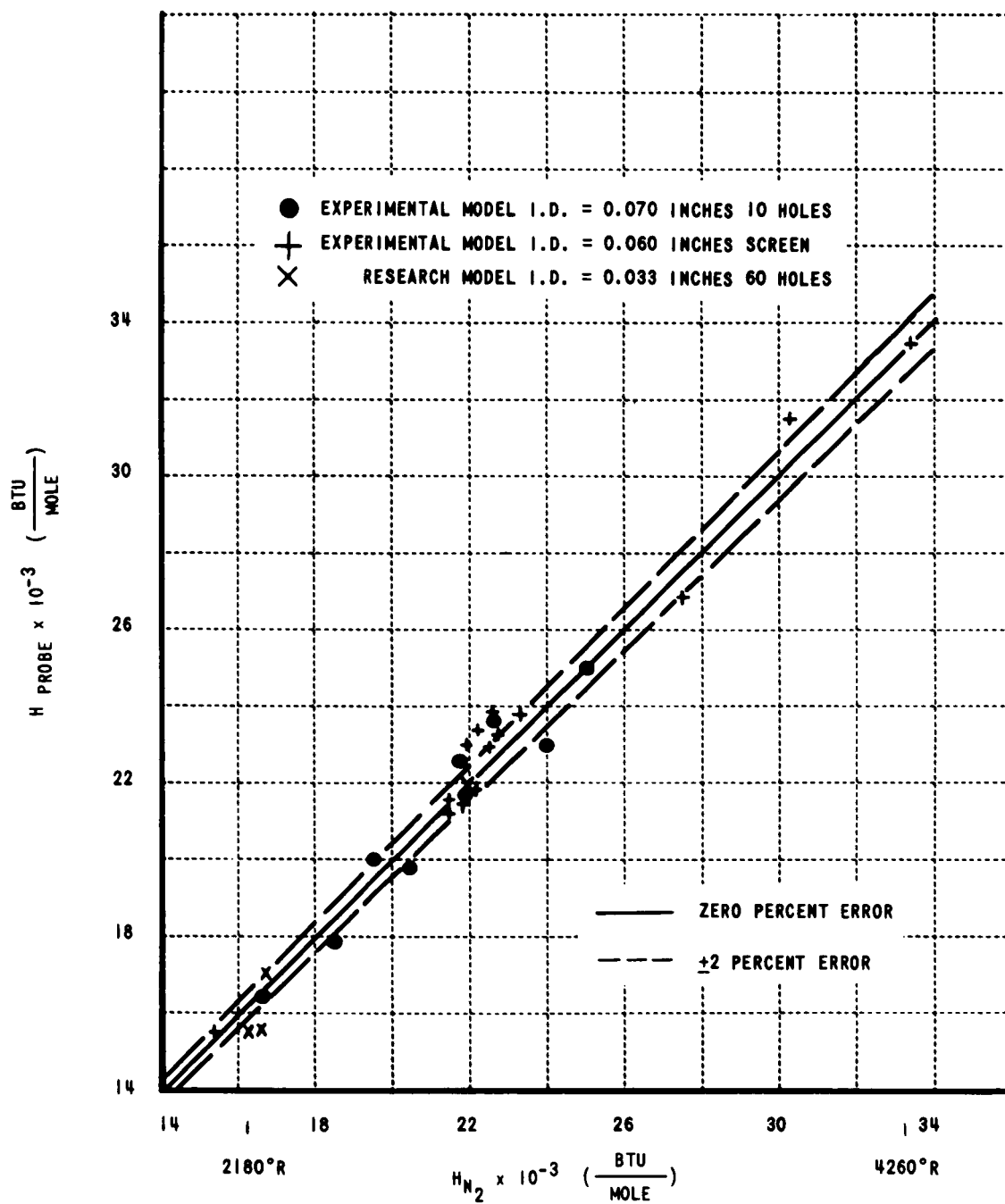


Figure 19 ENTHALPY DETERMINATION TEST DATA

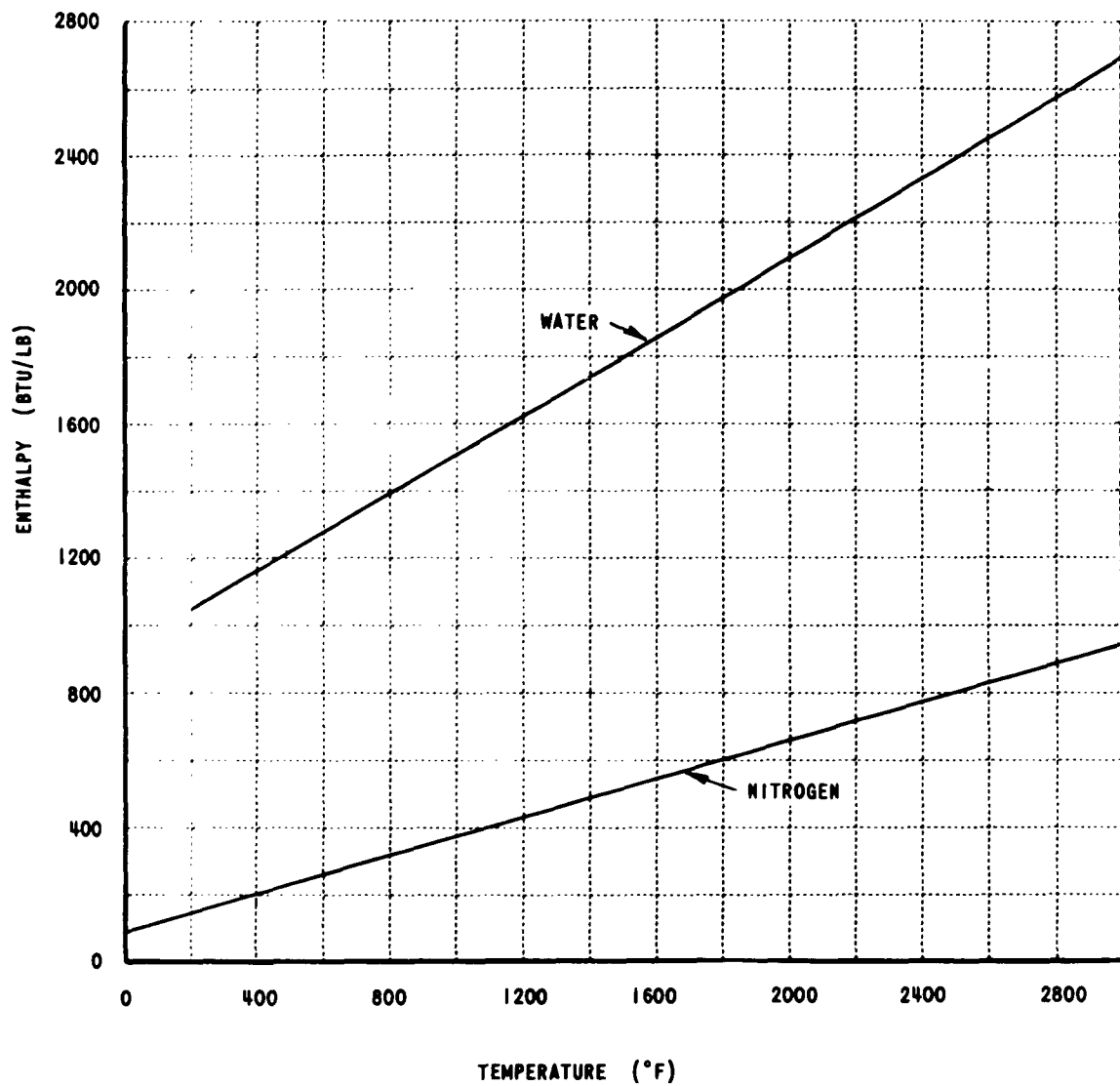


Figure 20 ENTHALPY VS TEMPERATURE FOR NITROGEN AND WATER

VII. VAPOR MIXTURE COMPOSITION MEASUREMENT

For the purpose of enthalpy measurement by the calorimetric technique investigated in this report, it is required that composition of the exit gas stream be determined. For the present considerations a two-component system (N_2 - H_2O) which consists of one condensable and one noncondensable gas is of interest. In the temperature range of operation, condensation of one species is a definite possibility hence operation at a temperature of about 300 °F is required. To meet the objectives of the over-all program the measurement must be continuous, have a response time of less than a second and have good accuracy in the 10-90 mole percent water range.

A survey of commercially-available gas-phase composition measurement instruments indicated that water vapor content of gas streams may be measured by using heat of absorption, thermal conductivity, infrared techniques, or gas chromatograph techniques. Each of these four techniques has basic shortcomings which negates its use for the intended measurement. A shortcoming common to all is the maximum operating temperature of the order of 120 °F. For the use intended, a specially fabricated instrument is required. Other more prohibitive shortcomings are as follows. The heat-of-absorption techniques are limited to concentrations of the order of three mole percent and extension to larger concentrations is prohibited by the rapid decay of the absorbing material due to the large amount of water present. The thermal conductivity measurement instruments have response times of the order of minutes and insufficient accuracy (2%) for the use intended. Instruments based on infrared measurement techniques have response times of the order of ten seconds and are limited to concentration levels of ten percent water vapor. The gas chromatograph techniques are essentially noncontinuous because the gas can be sampled only at approximately five minute intervals.

An analysis of the physical properties of the nitrogen-water vapor mixture indicated that the dielectric constant and the specific heat are physical properties attractive as quantitative measurement devices. Conceptual instrument designs based upon these properties were evaluated. The dielectric

constant, on the basis of superior response time characteristics, was selected for evaluation as a composition measurement parameter.

A. COMPOSITION MEASUREMENT BY USE OF DIELECTRIC CONSTANT

Theoretical development of equations for the dielectric constant of materials is given in many texts on physical chemistry (Reference 12 for example). The nitrogen-water gas mixture consists of molecules which possess only induced electric moments (nitrogen) and molecules which possess in addition a permanent electric dipole moment (water). The mixture is classified as a substance of low density and the electrical field is essentially static, i.e., the frequency is less than 10^{10} cycles/sec. For the general case of a gas molecule possessing a permanent dipole moment the dielectric constant is:

$$D = 1 + 4\pi N \frac{\rho}{M} \left(\alpha + \frac{M^2}{3kT} \right) \quad (22)$$

$$(D-1) \frac{M}{\rho} = 4\pi N \left(\alpha + \frac{M^2}{3kT} \right) \quad (22a)$$

The term on the right side of Equation (22a) determines the magnitude of the electric moment which may be expected to build additively from component partial electric moments. By equality, the left side term also is the sum of partials, hence:

$$(D_m-1) \frac{\bar{M}}{\rho} = Y_g (D_g-1) \frac{M_g}{\rho_g} + Y_c (D_c-1) \frac{M_c}{\rho_c} \quad (23)$$

Utilizing the ideal gas law this may be simplified to:

$$D_m - 1 = Y_g (D_g - 1) + (1 - Y_g) (D_c - 1) \quad (23a)$$

rearranging:

$$Y_g = \frac{(D_m - 1) - (D_c - 1)}{(D_g - 1) - (D_c - 1)} = \frac{D_c - D_m}{D_c - D_g} \quad (23b)$$

From Equation (21):

$$(D - 1) \propto \rho \propto \frac{P}{T}$$

The quantity $(D - 1)$ is shown as a function of T in Figure 21 for the gases nitrogen, water, and carbon dioxide.

The capacitance of a capacitor is given by:

$$C = \frac{\beta D A}{d} \quad (24)$$

in which A is the active plate area and d is the spacing between surfaces.

β is a constant based on configuration. For a plate type capacitor

$\beta = 0.0885$ when A and d are in centimeters. For a specific condenser:

$$C = KD \quad K = \frac{\beta A}{d} \quad (24a)$$

hence

$$Y_g = \frac{C_c - C_m}{C_c - C_g} \quad (25)$$

The mole fraction of nitrogen in the mixture may be evaluated by a simple lever law applied to the capacitance of the mixture, gas, and water vapor.

The capacitance of the mixture and gas may be evaluated by passing the respective vapor through the capacitor at known temperature and pressure.

The capacitance of the pure water vapor may also be obtained in this manner; however, it is difficult to obtain a pure water vapor. This difficulty may be circumvented by measuring the capacitance of a third readily available pure gas (carbon dioxide for example) whose dielectric constant is known. Capacitance of the water vapor at similar operating conditions is:

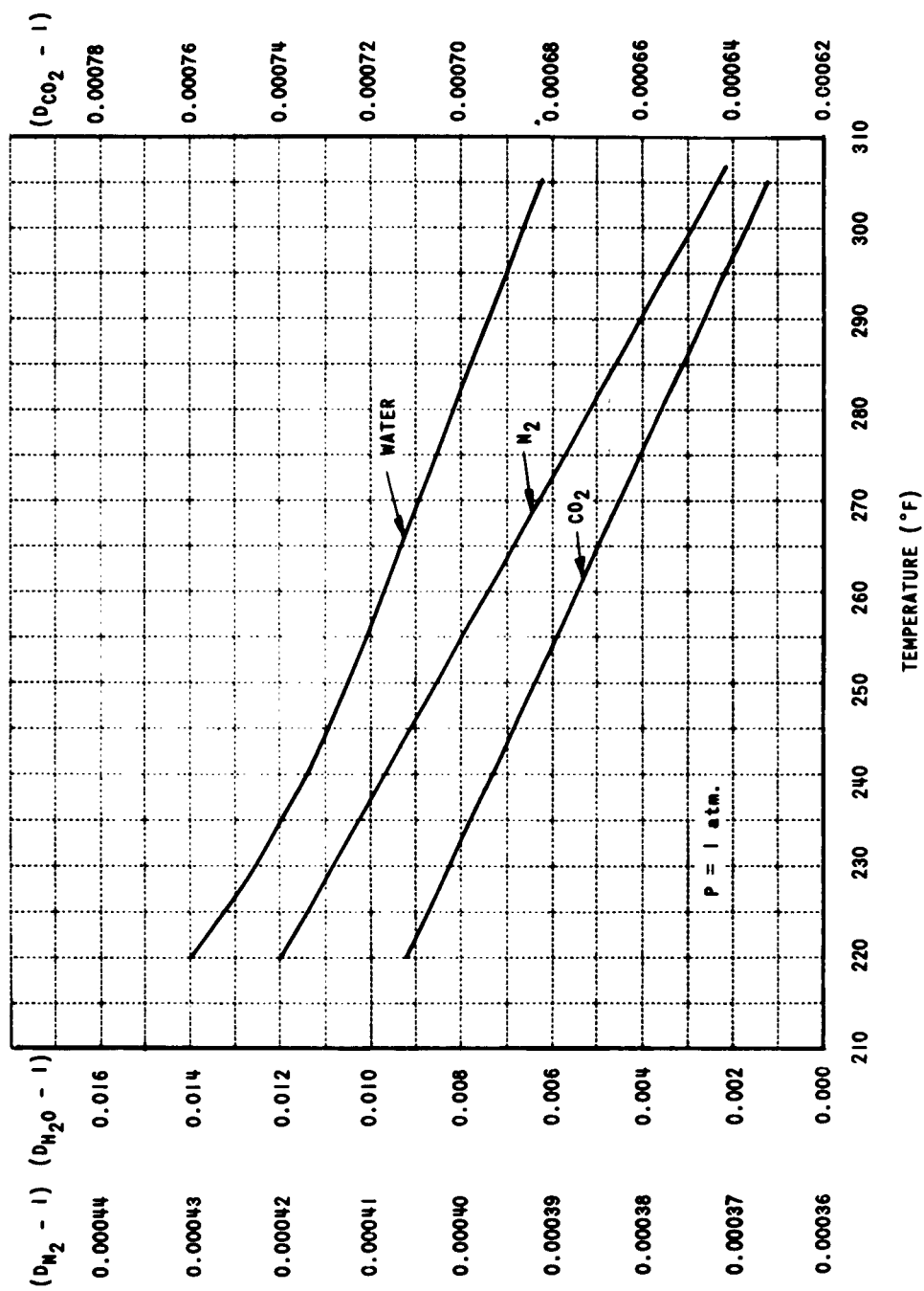


Figure 21 DIELECTRIC CONSTANT VS TEMPERATURE FOR NITROGEN, WATER VAPOR, AND CARBON DIOXIDE

$$C_{H_2O} = K D_{H_2O} = \left[\frac{C_{CO_2} - C_{N_2}}{D_{CO_2} - D_{N_2}} \right] D_{H_2O} \quad (26)$$

For the general case of operation at a pressure, P , different than standard atmospheric pressure, $P_o = 29.92''$ Hg, the equation for C_{H_2O} takes the form:

$$C_{H_2O}(P, T) = [C_{CO_2}(P, T) - C_{N_2}(P, T)] \left[\frac{1 + \frac{P}{P_o} [D_{H_2O}(P_o, T) - 1]}{\frac{P}{P_o} [D_{CO_2}(P_o, T) - D_{N_2}(P_o, T)]} \right] \quad (26a)$$

and for the general case:

$$C(P, T) = \frac{1 + \frac{P}{P_o} (D(P_o, T) - 1)}{D(P_o, T)} C(P_o, T) \quad (26b)$$

$D(P_o, T)$ may be evaluated from Figure 21. In using Equation (25) to determine the gas composition it is important that the pure gas capacitances be evaluated at the identical pressure and temperature conditions as the gas mixture conditions. These pure gas capacitance values may be inferred from calibration values taken at a specific temperature and pressure by use of the above equations. To eliminate need for accurate knowledge of the capacitance of the capacitor (i. e. the value of K) at a multitude of operating conditions, it is recommended that a calibration of the instrument be conducted before and after each period of testing.

B. ELECTRONIC READOUT SYSTEM FOR DIELECTRIC MEASUREMENT

The use of dielectric constant as the quantitative tool for measurement of vapor phase composition resolves itself into a measurement of capacitance of a specifically designed capacitor. For the purpose intended it is desirable to have a continuous measurement of the capacitance which may readily be

recorded on a conventional laboratory recorder. Conventional measurement of capacitance calls for placing the unknown capacitor across a calibrated variable capacitor and regulating the calibrated capacitor until a standard resonance frequency is obtained. The difference in readings of the calibrated capacitor is equal to the capacitance of the unknown capacitor. This technique does not lend itself to continuous recording of capacitance. The electronic system developed in this program for automatic recording of capacitance is as follows. A crystal oscillator and a cathode follower are used as a signal source to excite a high Q circuit (Q = ratio of reactance to resistance of the system). The Q circuit is adjusted to a point just off the resonance frequency of the signal source, care being taken to remain on the linear portion of resonance curve as shown in Figure 22. A change of capacitance due to change of dielectric properties of the gas in the capacitor is reflected as a change in frequency which, on the linear portion of the resonance curve, is directly proportional to a change in output voltage of the electronic system. The AC voltage developed in the Q circuit is biased negative, by a diode, an amount approximately equal to the amplitude of the AC voltage developed in the Q coil. This AC voltage is imposed upon one grid of a half of a dual triode and the AC signal is rectified between the grid and cathode of this tube. The other half of the dual triode has its grid maintained at a constant voltage, hence, a readout system connected between the cathodes shows a change proportional to the frequency of the circuit which in turn is proportional to the composition of the gas in the capacitor. Figure 23 shows the electronic circuit diagram for the system. A $0.1 \mu\mu f$ change of capacitance provides an output of over 100 millivolts. The millivoltage output of the system is recorded on a recording potentiometer.

The capacitor used for measurement of gas composition was designed to optimize the percentage of capacitance due to the test gas stream and the response time of the unit, which is directly related to the time required for gas to traverse the unit. The capacitor configuration is shown in Figure 24. This capacitor allows a capacitance change of $0.1 \mu\mu f$ (100 millivolts on the readout system) for a 100% change of gas stream composition. Capacitance

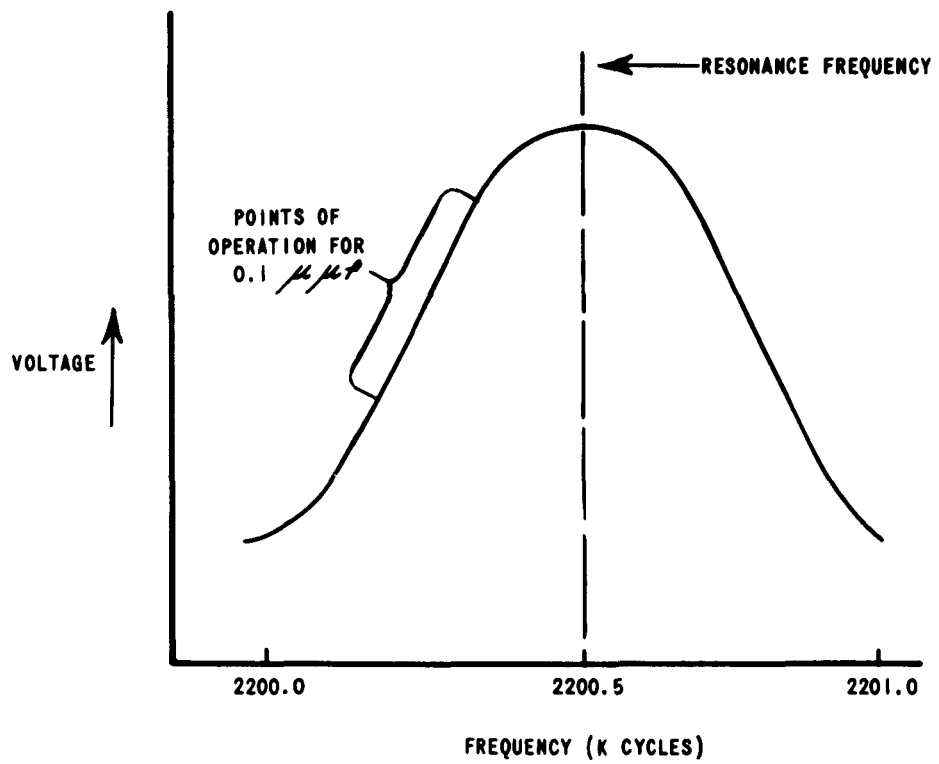


Figure 22 TYPICAL RESONANCE CURVE FOR A HIGH Q CIRCUIT

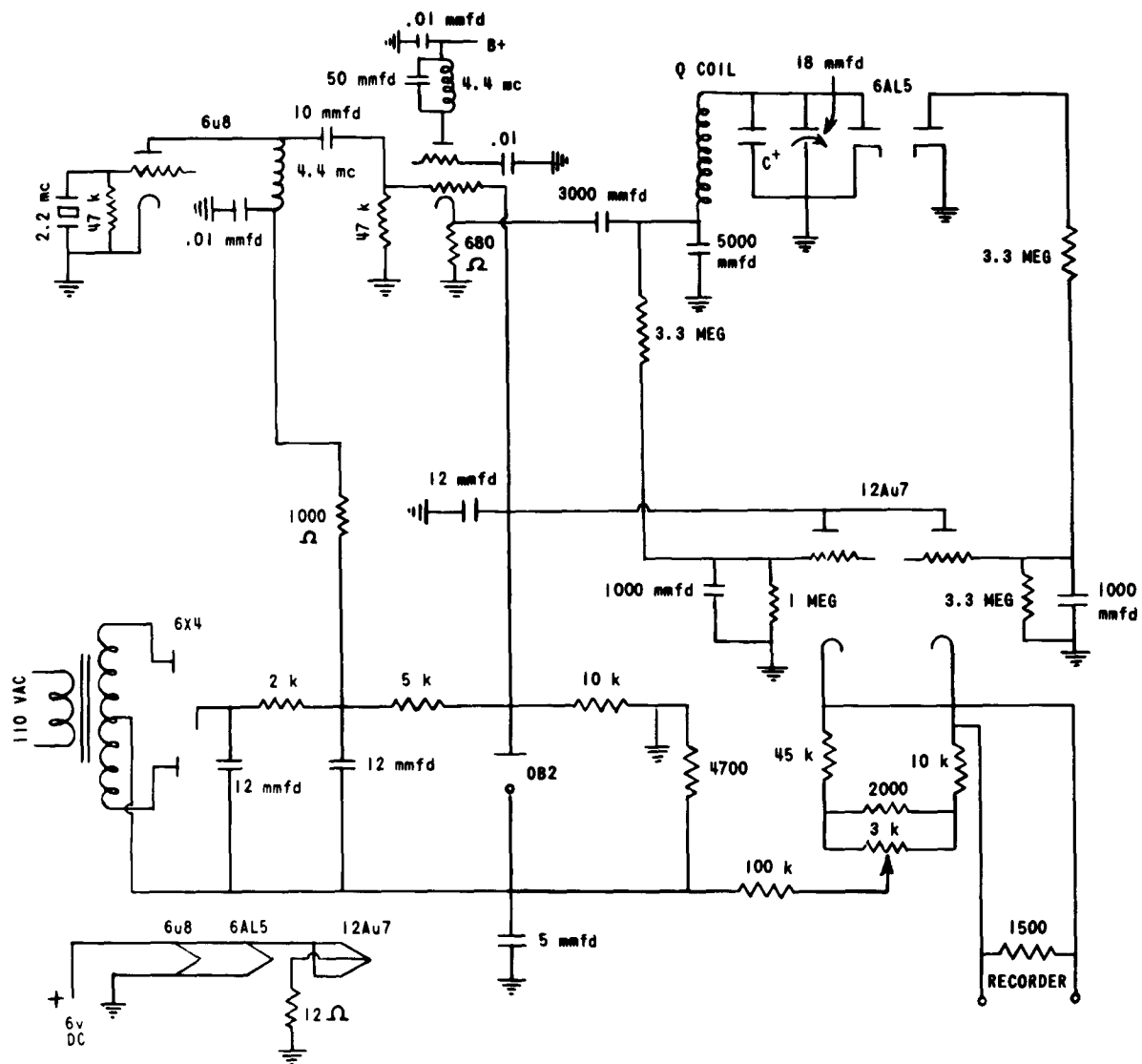


Figure 23 ELECTRONIC CIRCUIT FOR READOUT SYSTEM OF VAPOR COMPOSITION INSTRUMENT

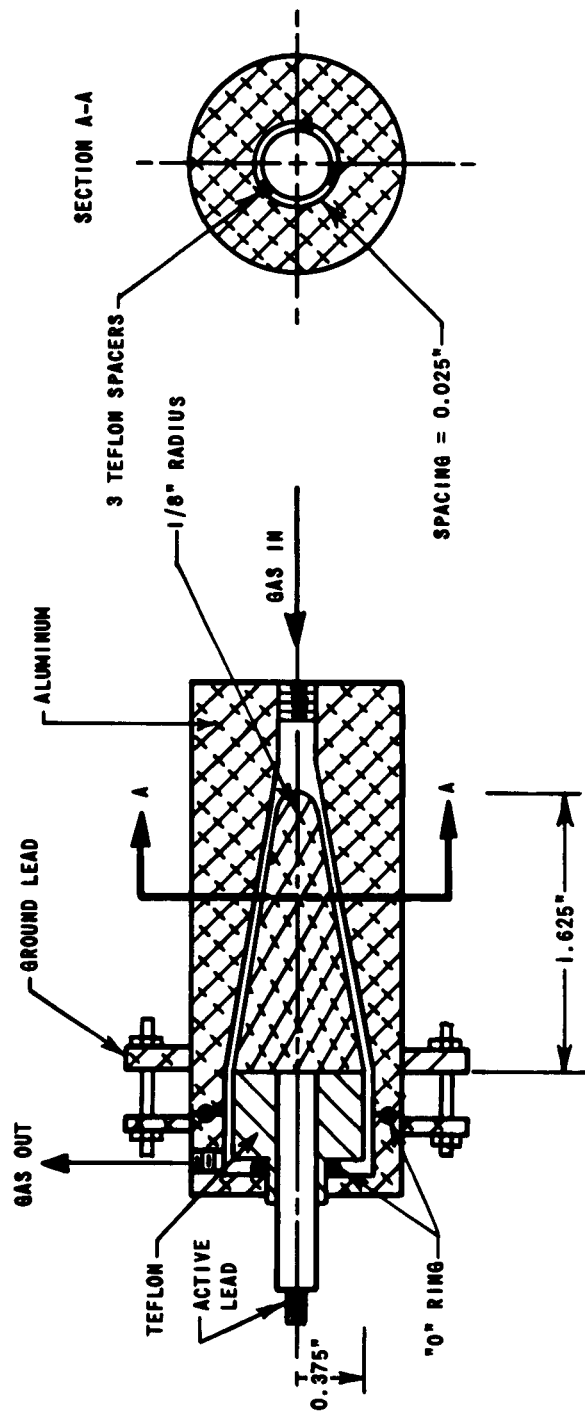


Figure 24 ASSEMBLY DRAWING OF CAPACITOR

of the unit is $23 \mu\mu f$ and the unit has a flow traversal time of one-half second at a flow rate of 100 cc/min which is the minimum rate of flow expected to be drawn from the gas-sampling tube of the enthalpy probe. For most enthalpy probe operating conditions the response time of the dielectric vapor composition measuring instrument is of the order of a second.

The instrument was initially evaluated by using the gases air, oxygen, nitrogen, helium, carbon dioxide, and acetylene. The measured dielectric properties of these gases compared favorably with values taken from Reference 14. The maximum error encountered was two percent. Experience gained in operation of the instrument has shown composition measurements must be made by making all component measurements at the same pressure level. This is due to the fact that the capacitor is sealed with an "O" ring which allows slight movement (due to changing internal pressure) of the conical core which causes slight changes in the capacitor spacing, hence the value of K is not constant as required for validity of Equations (24a) and (25). This problem can be overcome in redesign of the capacitor. For present operation, the pressure level of the calibrating gases (CO_2 and N_2) is adjusted to the pressure level of the gas mixture whose composition is desired. A second problem encountered in operation was a severe instability problem of the readout millivoltage. A major source of this instability was found to be fluctuations in the input voltage. After taking precautions to minimize the input fluctuations, the severity of the readout instability was greatly reduced, although not completely eliminated. For present operation, the instrument calibration, by passing CO_2 and N_2 through the capacitor, must be repeated at intervals of approximately one minute. It is believed that further reduction in readout instability may be attained by taking precautions against mechanical vibration, thermal currents within the electronic system and by providing further isolation of components. The goal of this phase of the program is to provide an instrument which requires calibration only before and after tests, hence, operation for periods as long as an hour is desirable.

The random variation of the millivoltage output about the mean value is about one percent of scale or about one millivolt. It is believed that gas mixture composition is presently measured to within two percent and that as experience and skill are gained in the operation of this instrument, and if the above mentioned improvements in the system are incorporated, the level of error may be decreased to less than one percent.

VIII. SUMMARY

A technique of making a calorimetric enthalpy measurement of high energy content gases, by utilizing an evaporating liquid film to cool a gas sample, has been investigated. Temperature and composition of the cooled gas sample provide the major information for an energy balance on the system which in turn provides the total enthalpy of the entering gas. The system has distinct advantages over previous calorimetric enthalpy measurement techniques inasmuch as it lends itself to a considerable degree of miniaturization and it may be operated continuously, overcoming a serious disadvantage of previous techniques. Use of water as the evaporating film coolant in an arc-heated nitrogen atmosphere has been considered in detail. A research model of the instrument, designed to measure an enthalpy of 15,000 Btu/#, has been fabricated. This instrument has an outside diameter of 0.1" and is capable of operating continuously if the gas composition is measured continuously.

The accuracy of the technique has been demonstrated by a series of enthalpy determinations made at temperature levels between 2200°R and 4300°R. These tests show an average deviation of 2.3 percent (range = 0 to 6.0 percent) between the measured enthalpy and that obtained by a comparison technique.

The greatest difficulty involved in this technique of enthalpy determination is continuous measurement of gas mixture composition. To alleviate this difficulty, an instrument using the dielectric constant of the mixture as a quantitative tool has been fabricated and tested. Although problems have been encountered with long-term stability, it is believed that this instrument has the potential of providing the required continuous composition measurement and that this potential may be realized with some changes of the existing instrumentation.

Results to date show the evaporating film coolant technique of enthalpy measurement to be accurate, capable of continuous operation and conducive to fabrication of miniature instruments.

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APPENDIX A

LITERATURE SURVEY

The following literature concerning temperature and enthalpy measurement in high energy content gas streams have been reviewed during a literature survey conducted as part of this program.

I

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APPENDIX B

GAS-LIQUID INTERFACE CONDITIONS

The following approximate analysis allows determination of the liquid-gas interface temperature at any point within the gas-sampling tube. In particular, the value at point C in Figure 1 is of importance in the total enthalpy computation by Equation (1e).

Consider the gas velocity at the interface to be of order zero, then by equimolal counterdiffusion the velocity of water vapor leaving the interface is given by:

$$v_c = - \frac{D_{c-g}}{1-y_c} \frac{dy_c}{dr} = \frac{D_{c-g}}{1-y_c} \frac{dy_g}{dr} \quad (B-1)$$

Multiplying by density, the mass flux of coolant vapor leaving the interface is:

$$\rho_c v_c \Big|_i = \frac{(\rho_c D_{c-g})_i}{1-y_{ci}} \frac{dy_g}{dr} \Big|_i \quad (B-2)$$

The heat flux arriving at the interface may be written in a similar form:

$$\frac{q}{A} \Big|_i = \frac{k}{C_p} \frac{dH}{dr} \Big|_i \quad (B-3)$$

If the Prandtl and Lewis numbers are equal to one, the profiles for velocity, enthalpy, and composition by similarity become:

$$\frac{u}{u_o} = \frac{H-H_i}{H_o-H_i} = \frac{y_{ci}-y_c}{y_{ci}-y_{co}} \quad (B-4)$$

in which the subscript "o" indicates the centerline of the tube. Combining Equations (B-1), (B-2) and (B-3):

$$\rho v_c \Big|_i = \frac{y_{c,i} \dot{Q}/A \Big|_i}{H - H_i} \left(\frac{y_{g_0} - y_{g,i}}{1 - y_{c,i}} \right) \quad (\text{B-5})$$

If there is negligible heat loss at the liquid-solid interface:

$$\rho v_c \Big|_i \lambda_{c \text{ vap.}} = \dot{Q}/A \Big|_i \quad (\text{B-6})$$

Combining with Equation (B-5) yields

$$\frac{1}{\lambda_{c \text{ vap}}} = \frac{1 - y_{g,i}}{H_0 - H_i} \left(\frac{y_{g_0} - y_{g,i}}{y_{g,i}} \right) \quad (\text{B-7})$$

$$\frac{1}{y_{c,i}} = \frac{\lambda_{c \text{ vap.}} (y_{c,i} - y_{c_0})}{H_0 - H_i} + 1 \quad (\text{B-7a})$$

By Dalton's law of gas mixtures:

$$P_T = P_c + P_g$$

$$P_c = Y_c P_T$$

$$y_c = \frac{Y_c M_c}{Y_c M_c + (1 - Y_c) M_g} \quad (\text{B-8})$$

$$\frac{1}{y_c} = 1 + \frac{M_g}{M_c} \left(\frac{1}{Y_c} - 1 \right)$$

hence at the interface:

$$\frac{1}{y_{c,i}} = 1 + \frac{M_g}{M_c} \left(\frac{P_T}{P_{c,i}} - 1 \right) \quad (\text{B-9})$$

Equating Equations (B-7a) and (B-9):

$$\frac{\lambda_{c,vap} [y_{ci} - y_{co}]}{H_o - H_i} = \frac{M_g}{M_c} \left(\frac{P_T}{P_{ci}} - 1 \right) \quad (\text{B-10})$$

Equation (B-10) contains the gas stream properties at the centerline of the tube while the measured parameters are averaged values. By Equation (B-4):

$$\frac{y_{ci} - y_{co}}{H_o - H_i} = \frac{y_{ci} - y_c}{H_o - H_i} = \frac{y_{ci} - \bar{y}_c}{\bar{H} - H_i} \quad (\text{B-4a})$$

Substitution into Equation (B-10) yields:

$$\frac{\lambda_{c,vap} [y_{ci} - \bar{y}_c]}{\bar{H} - H_i} = \frac{M_g}{M_c} \left(\frac{P_T}{P_{ci}} - 1 \right) \quad (\text{B-10a})$$

The enthalpy of a gas mixture is given by:

$$H = y_c H_c + (1 - y_c) H_g \quad (\text{B-11})$$

Equation (B-10a) then becomes:

$$\frac{\lambda_{c,vap} [y_{ci} - \bar{y}_c]}{\bar{H}_g - H_{gi} + \bar{y}_c (\bar{H}_c - \bar{H}_g) - y_{ci} (H_{ci} - H_{gi})} = \frac{M_g}{M_c} \left(\frac{P_T}{P_{ci}} - 1 \right) \quad (\text{B-10b})$$

This equation implicitly involves the liquid-gas interface temperature and this temperature may be evaluated by an iterative procedure. The quantities \bar{H}_g , \bar{H}_c and \bar{y}_c are measured quantities at the gas exit point (point C of Figure 1). Selection of an interface temperature allows evaluation of P_{ci} , H_{ci} , H_{gi} , and $\lambda_{c,vap}$. The parameter y_{ci} is computed from Equation (B-9). This information allows iterative solution of Equation (B-10b) to determine the interface temperature. Table 3 contains a tabulation of required parameters for the $\text{N}_2 - \text{H}_2\text{O}$ system at 1 atmosphere of pressure.

TABLE 3
INTERFACE PROPERTIES AT P = 1 ATMOSPHERE

T_i	λ	P_i	$\frac{1}{y_{c_i}}$	y_{c_i}	H_{H_2}	H_{N_2}
(°F)	(Btu/#)	(psi)	$\frac{\#mix.}{\#c}$	$\frac{\#c}{\#mix.}$	$\frac{(Btu)}{\#}$	$\frac{(Btu)}{\#}$
150	1008	3.71	5.5	0.18	1126	151
160	1002	4.74	4.3	0.23	1130	154
170	996.9	5.99	3.2	0.31	1134	157
180	990.2	7.51	2.4	0.41	1138	159
190	984.1	9.34	1.9	0.53	1142	161
200	977.9	11.52	1.4	0.71	1146	163
210	971.6	14.12	1.06	0.94	1150	166
212	970.3	14.70	1.00	1.00	1151	167

Table 4 contains a tabulation of interface conditions for a variety of measured gas conditions.

TABLE 4
INTERFACE TEMPERATURE AND COMPOSITION FOR THE
N₂ - H₂O SYSTEM AT ONE ATMOSPHERE PRESSURE

T	\bar{y}_c									
	0.1		0.3		0.5		0.7		0.9	
°F	T_{c_i}	y_{c_i}	T_{c_i}	y_{c_i}	T_{c_i}	y_{c_i}	T_{c_i}	y_{c_i}	T_{c_i}	y_{c_i}
500	149.5	0.174	176.0	0.364	191.5	0.555	201.0	0.735	209.0	0.913
1000	166.0	0.272	184.0	0.446	195.0	0.614	203.0	0.775	209.3	0.928
1500	174.5	0.348	189.0	0.515	198.0	0.672	205.0	0.820	209.5	0.937
2000	180.1	0.414	192.0	0.570	199.8	0.707	205.5	0.833	210.0	0.947
2500	185.5	0.475	195.0	0.617	201.5	0.742	206.5	0.855	210.2	0.954

APPENDIX C

AN APPROXIMATE EQUATION OF STATE FOR NITROGEN IN THE DISSOCIATED AND WEAKLY IONIZED CONDITION

The thermodynamic properties of high temperature nitrogen are available in tabular form in Reference C-1 in the temperature range 2000 to 8000 °K and a density range of 10^{-3} to 10 times standard atmospheric density. For many engineering applications an approximate analytical relationship describing the pressure, density, and energy content of the gas is useful. At low temperature levels, temperatures where dissociation is not important, many generalized equations of state exist, the simplest being the ideal gas law. When dissociation takes place, the energy content of the gas is no longer measured by gas temperature because energy is also being absorbed in a chemical reaction, hence enthalpy is used to define the energy content of the gaseous system.

Figure 25 shows data of Reference C-1 plotted in the form $\frac{P}{P_0} \cdot \frac{\rho_0}{\rho}$ vs H/RT_0 for various values of ρ/ρ_0 . Note that the data are independent of ρ/ρ_0 for values of H/RT_0 less than 58 ($T < 4000$ °K). Figure 26 shows the data of Figure 25 plotted as a function of P/P_0 . A reference parameter, $H_1 = 58 RT_0$, has been introduced on the abscissa. Definition of base properties allows these data to be fitted to equations by curve fitting techniques.

$$P_1 = 1 \text{ atm}$$

$$\rho_1 = 8.65 \times 10^{-5} \text{ gm/cc}$$

$$H_1 = 58 RT_1$$

$$R = 1.987 \text{ cal/gm-mole } ^\circ\text{K}$$

$$T_1 = 288.1 \text{ } ^\circ\text{K}$$

$$27 < \frac{H}{RT_1} \leq 58 \qquad \frac{P}{P_1} \cdot \frac{\rho_1}{\rho} = \left(\frac{H}{H_1} \right)^{0.89} \qquad \text{(C-1)}$$

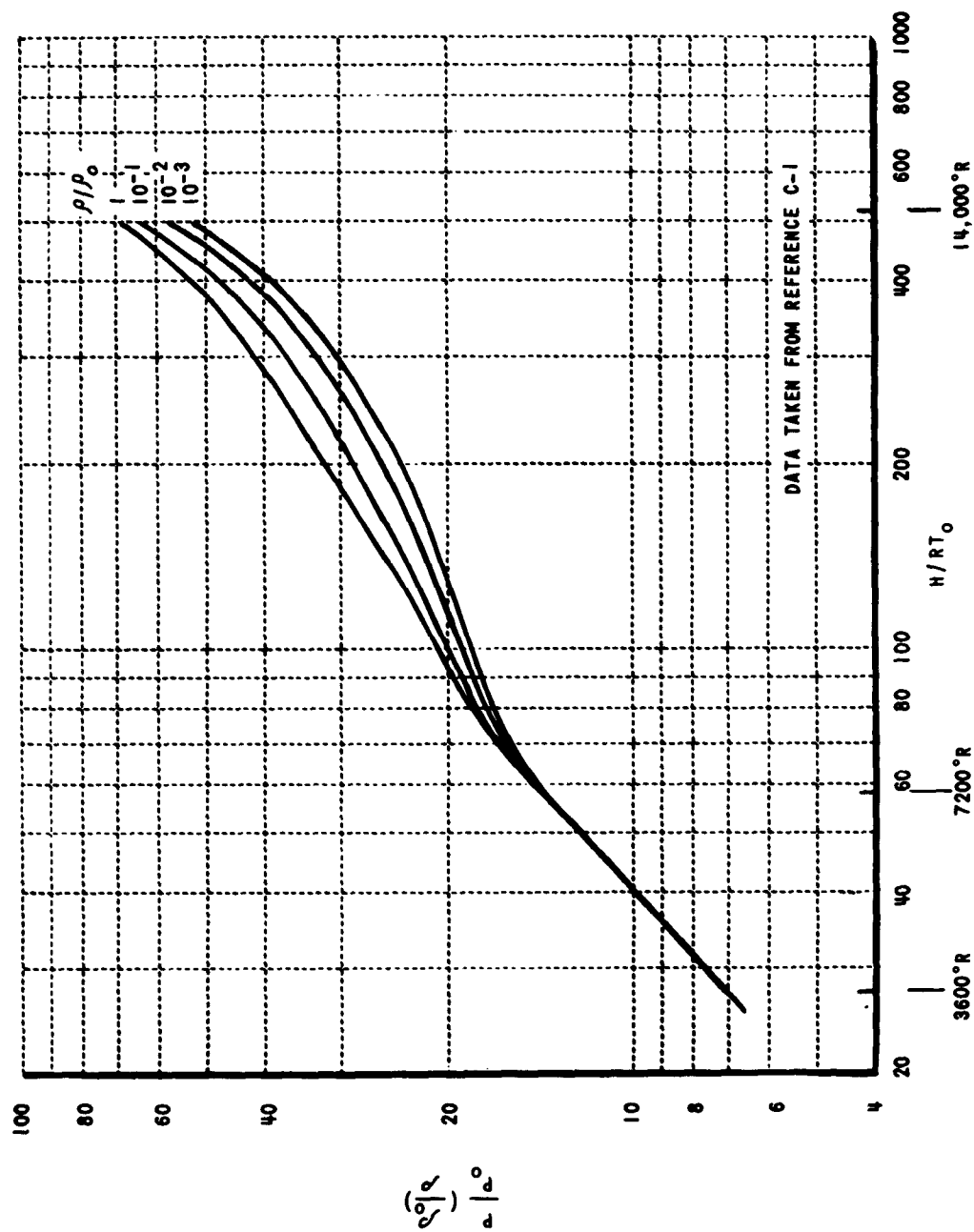


Figure 25 $\frac{P}{P_0} \left(\frac{\eta_{sp}}{c} \right)$ VS $\frac{H}{RT_0}$ FOR NITROGEN

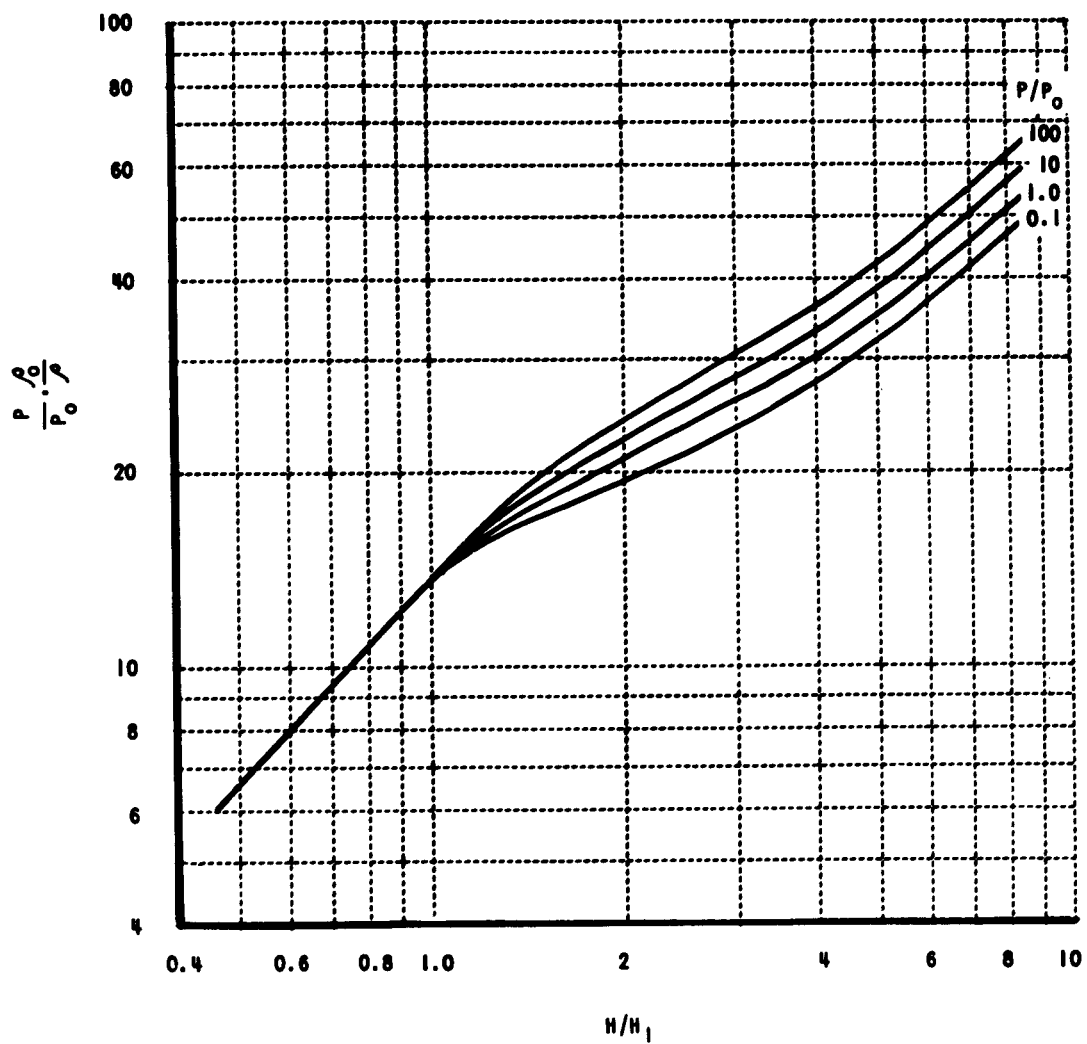


Figure 26 $\frac{P}{P_0} \cdot \frac{\rho_0}{\rho}$ vs $\frac{H}{H_1}$ FOR NITROGEN

$$58 \leq \left(\frac{H}{RT_1} \right) \leq 500 \quad \frac{P}{P_1} \cdot \frac{\rho_1}{\rho} = \left(\frac{H}{H_1} \right)^{0.615 + 0.040 \log_{10} P/P_1} \quad (C-2)$$

These equations have been compared with the tabulated data of Reference C-1 and the Mollier Diagram given in Reference C-2. Equation (C-1) is accurate within one percent while Equation (C-2) indicates an average error of 4.2 percent with a range of error of 0.2 to 8.8 percent. The useful limits of the equation are set by:

$$58 < H/RT_1 < 500$$

$$0.02 < P/P_1 < 200$$

The pressure dependence of the exponent of Equation (C-2) is weak, hence an average pressure may be used in the exponent for processes involving pressure change.

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<p> Aeronautical Research Laboratories, Wright-Patterson AFB, O. AN EVAPOR- ATING FILM CALORIMETRIC ENTHALPY PROBE by F. C. Haas, Cornell Aero- Laboratory, Inc., Buffalo, N.Y. Feb- 1963. 44p. incl. illus. tables. [Project 7063; Task 7063-01] (Contract AF 33(657)-7774) (ARL 63-47) Unclassified Report </p> <p> A calorimetric enthalpy probe of small size, capable of continuous operation in a high temperature, high heat flux environment, such as an arc, is des- cribed. The instrument operates by removing a sample from a hot gas stream stream and cooling it by evaporative film cooling until the temperature </p> <p style="text-align: right;">(over)</p>	<p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p>
<p> of the gas sample is low enough for measurement by conventional means. The composition of the cooled gas is measured and the total enthalpy of the hot gas entering the instrument is determined by an energy balance tech- nique. The structure of the instru- ment may be maintained at a tolerable temperature level by forced convec- tive cooling or by evaporative film cooling. </p> <p style="text-align: right;">(over)</p>	<p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p> <p>UNCLASSIFIED</p>